Merging Aerial Synthetic Aperture Radar (SAR) and Satellite Multispectral Data to Inventory Archaeological Sites

Introduction

Outcomes attributable to the research funded through the 2005 NCPPT grant[1] can be summarized as follows:

1) Protocols for the detection of archaeological sites through the analysis of *commercially available* synthetic aperture radar (SAR) and multispectral images. Previously existing protocols for site detection through image analysis had utilized images generated from synthetic aperture radar (SAR) data collected by an experimental JPL/NASA platform.
2) Strong evidence that the revised protocols can produce archaeological site signatures in environments characterized by moderate ground cover (i.e., tall grasses, large and dense shrubs, some forested areas usually comprised of small trees) and generally severe terrain. Previous protocols were developed and tested in an environment that was generally flat and covered by light vegetation (i.e., grasses and small shrubs).

In addition, refinement of protocols facilitated the development of experimental software that automates the protocols described above. Also, the research stimulated contributions in kind from a variety of organizations and individuals for the continued refinement of prototypical software.

Protocols for the use of synthetic aperture radar (SAR) deployed by airborne platforms for wide-area, planning-level inventories of archaeological sites and other features of archaeological and historic interest had previously been developed by Douglas C. Comer, of CSRM, Inc., and Ronald G. Blom, of JPL/NASA (2007a, 2007b, 2007c), in a multi-year project funded by the Department of Defense Strategic Environmental Research and Development Program (SERDP). These protocols covered all aspects of using airborne SAR for archaeological survey, from flight planning to the practical use of signatures in cultural resource management. The most essential of these SAR protocols are repeated here. Those that have not been much modified are given in abbreviated form. Protocols that have undergone substantial modification are treated more fully. The most important changes have been made to protocols for the statistical analysis of images for anomalous sensor returns that can be spatially linked to the locations of archaeological sites or features of archaeological interest.

For reasons and in ways that will be described, statistical analysis procedures initially applied to SAR images were tested, first during the SERDP research, and

1 The National Center for Preservation Training and Technology (NCPTT) provided funding for this research to the Santa Catalina Island Conservancy. The Conservancy contracted with Cultural Site Research and Management (CSRM) to carry out this research.

more completely in research at the current test area of Santa Catalina Island, for their efficacy in the analysis of multispectral images. Ultimately, in an effort that was supplemental to the NCPTT research and which was funded by CSRM, this led to automating analytical protocols by means of prototypical software. The software, although in its embryonic developmental stage, reduces the time required to exercise statistical analytical protocols from roughly five hours to approximately 15 seconds. Many of the problematic aspects of image analysis for archaeological site signature development can be addressed by the use of this software, in that most involve altering analytical parameters in small ways that exert a large influence of results. Because altering, for example, the size of the area within which samples are taken, or rescaling images, or utilizing simple image enhancement algorithms required additional hours of analytical times when calculations were performed using a sequence of grid algebra calculations, it is probable that signatures reported here could still be improved. In the future, the newly developed software will permit the researchers to establish optimal parameters for signature development. Nonetheless, the results so far have been enough to demonstrate the utility of the protocols. For unrelated reasons, but fortunately, this research utilized *commercially obtained* synthetic aperture radar (SAR) and multispectral data sets. Because of this, our results are much more replicable than if they were based upon images produced by the experimental JPL/NASA platform AIRSAR, as was the case with the SERDP research. While AIRSAR collected SAR data at a number of areas and this data has been archived, AIRSAR has been grounded by NASA as it realigns it goals under direction from the current federal administration. Thus, not only will other areas not be covered, but also the computing resources necessary to render SAR data into the images that can be analyzed by the SERDP protocols will soon be eliminated.

The protocols presented here are used to develop statistically-determined site signatures. As such, these signatures identify areas where sites are significantly more likely to be located than to be absent, and areas where sites are significantly more likely to be absent than to be present. These site signatures are based in *empirical* data, more specifically, measurements obtained by use of SAR and multispectral sensors. As such, *they should not be confused with predictive models*, which are developed from *historical* data.

To achieve this outcome, stock SAR and multispectral images were post-processed in ways described below to develop other image layers that experience had suggested would be more useful than the original images in identifying the locations of archaeological sites. These image layers were generated by an algorithm that manipulated numerical values extracted from image pixels. By means of statistical testing, certain pixel values in image layers were found to be associated with archaeological sites. Postulated links between pixel values that were found to be statistically associated with archaeological sites and the sites themselves will be presented in this report. All such links involve environmental changes produced by human occupation or use.

It is possible that some environmental changes, such as clusters of material used to build habitations (on Santa Catalina Island, for example, these were often clusters of stones of approximately the same size), or scatters of artifacts, bone, or shell, might be seen by a determined observer on the ground. Direct observation, however, would necessitate traversing a rugged landscape through exuberant vegetation that conceals artifact scatters, dark midden soils, and landscape alteration that marks archaeological sites. Even in the absence of ground cover, more subtle changes produced by human use of an area, such as alteration to soil composition or moisture content because of the introduction of organic material and ash by prehistoric occupants would probably not be readily visible to a human being standing on the site. Soil differences, and vegetative differences produced by soil differences, are much more visible in aerial or satellite imagery, because of the synoptic factor introduced by an aerial perspective, which renders patterns, rather than individual features, more noticeable. Secondary environmental changes seen in this way are sometimes more distinct than primary ones. In the case of altered soils, for example, vegetation that is anomalous to surrounding vegetation in terms of plant type or vigor is common.

Problems, Lessons, and Opportunities

The SAR data that was initially utilized in the SERDP research was obtained by use of the JPL/NASA platform AIRSAR, a DC-8 aircraft. This was the most versatile SAR platform in the world, having the capability to collect multi-band (P-, L-, and C-band) data that could be polarized in several different ways (see Fig. 1, below). The AIRSAR platform, however, was mothballed just prior to completion of the SERDP research in 2005. This was done because NASA reprogrammed funds from the earth science sector to a program that is intended to place humans on Mars several decades from now.

Instrument	Frequency band	Bandwidth (MHz)	Band Length (cm)	Single-look range resolution (m)	Polarizations	Interfero-metric	Pixel Size in This Study, After Orthorectification and Post-Processing
AIRSAR	P	20	68	7.5	HH, VV, HV, VH	No	5,5
AIRSAR	L	40, 80	25	3.7, 1.8	HH, VV, HV, VH	Yes	5,5
AIRSAR	C	40	5.7	3.7	HH, VV, HV, VH	Yes	5,5

GeoSAR	P	160 (max)	86	0.9	HH, HV or VV & VH	Yes	N/A
GeoSAR	X	160	3	0.9	VV	Yes	3,3 DEM 5,5 Image

Fig. 1 AIRSAR and GeoSAR bands, compared

The decommissioning of AIRSAR was anticipated at NASA. During the same period that this eventuality moved into the realm of certainty, it became clear that the SERDP research would, indeed, develop protocols for the use of SAR that could be applied in ways that would accomplish the desired outcome of the SERDP research: to devise a way to conduct wide-area archaeological inventory of military lands utilizing SAR data. Protocols for integrating supplementary data sets had been identified at the outset of the research as one of its ten technical objectives. Therefore, the Co-PIs of the SERDP project began testing the suitability of other data sets to the goals and desired outcome of the research. We did this at our SERDP test area, San Clemente Island, California, which is located in the Pacific about 90 kilometers west of San Diego. In doing this, historic aerial photographs at the National Archives and Record Administration (NARA) were examined. Color infrared transparencies taken of San Clemente Island in the mid-1970s were obtained there. These were scanned and brought into the project geographical information system (GIS). This could be done with great accuracy by using the C-band DEM to orthorectify the images. When the orthorectified images were examined, a number of known archaeological sites were clearly discernible. Historic aerial black and white photographs that had been taken in the 1950s were also obtained in this way. When these were orthorectified with the C-band DEM and placed in the GIS, many of the known archaeological sites were also visible in these. In examining the historic aerial images, then, we established two things: The first was that, because many archaeological sites were so visible in the infrared imagery, there was clearly reason to test multispectral imagery as a part of the signature development, so long as it included an infrared or near infrared channel. Further, this sort of modern multispectral imagery is generated from data collected by electronic sensors, as opposed to the infrared film that had produced the archived infrared images. That being so, analytical possibilities were greater. For example, the IKONOS satellite collects four bands of data: red, green, blue, and near-infrared. Standard algorithms have been developed that enhance the analytical utility of infrared or near-infrared imagery by factoring in red, green, and blue returns.

Secondly, we gained a good sense of just how dramatically the vegetation on San Clemente Island had changed over a fifty year period. In the 1950s, when the black and white aerial photos had been taken, almost all vegetation, with the exception of some cacti, had been consumed by feral goats on San Clemente Island. Therefore, the rock scatters and dark midden soils associated with habitation sites were often clearly visible in the black and white aerial imagery. Since the 1950s, the feral goats had gradually been removed. As this occurred, various vegetative communities had moved in, following a complicated succession. At archaeological sites, grasses began to grow in the richest organic soils, invariably located in the center of the sites. Grass seeds provided an attractor to mice. Mice were hunted by the San Clemente Island Fox and other predators, notably the San Clemente Island Shrike. Both of these were listed species. As they made a comeback, these predators increasingly disturbed soils at archaeological sites as they pursued their prey. Since grasses grow well in disturbed soils, the very center of many archaeological sites on the island remained covered by grasses. Other plant species on the sites were changing, however. Morning glory, once very rare on the island, was reemerging. When cacti were practically the only plants on the island, they grew in disproportionate numbers on the archaeological sites, because of the rocks and the moister soils there. As morning glory plants increased in number, the vines grew over the cactus plants, and gradually killed many of them by cutting off sunlight and competing for moisture. Thus, in most of San Clemente Island, many archaeological sites were covered by thick stands of grasses in the center, and ringed with cactus and morning glory. This mixture and arrangement of plant species was not invariable. It changed according to soil characteristics and aspect, among other variables. Nonetheless, the general pattern held: a plant type (usually grasses) in the center of the site, with a perimeter of a different sort or sorts of plants that were different from the general plant complex around the site. Conversations with botanists doing research on San Clemente Island increased our awareness of such patterns. We could often see this sequence when comparing the 1950s aerial to the 1970s infrared images, and then to the recent aerial and satellite photographs that we placed in the project GIS. We also determined that the stage of succession that was current when our SAR and multispectral data sets were collected was hardly final. In some areas, for example, large shrubs of the genus *Baccharis* have become increasingly common from 2004 to the present. The plant seems to appear in disproportionate numbers at archaeological sites that have especially rich organic soils. Therefore, peculiarities in the vegetative cover of archaeological sites continue to set them apart from the surrounding landscape. While the precise nature of these differences can be expected to change through time, they should continue. This is because the soil environment at the archaeological sites has been altered by human use. Similarly, the difference in vegetative cover at an archaeological site can be more obvious, or less, depending upon the time of year, yet a difference generally persists.

Much of what we learned about San Clemente Island landscape and site morphology was relevant to Santa Catalina Island. On Santa Catalina Island, vegetation is also changing because of removal of introduced species. Two introduced species that have done considerable damage to the native ecology of the island are feral goats and pigs. Removal of these two species, alone, has allowed a resurgence of vegetation in general, and changes in the vegetative complex in many areas. One can reasonably expect that while vegetative cover on archaeological sites will change with the season or through time, it remains anomalous to surrounding vegetation. SAR is capable of detecting anomalous vegetative structure, and multispectral data can be used to identify vegetation that is more or less vigorous than surrounding vegetation.

Therefore, prospects were good for the use of SAR data sets obtained from an airborne commercial platform (GeoSAR) and multispectral data sets collected by the IKONOS (commercial) satellite and the NASA ASTER satellite. We began developing protocols for the use of these data sets even prior to the conclusion of the SERDP research. (We also submitted our NCPTT grant application during this time period.) As our SERDP research continued, we found that the statistical analysis protocols that we had developed for use with AIRSAR data also worked well with the commercially available data (both SAR and multispectral) at our SERDP test area, San Clemente Island, California. Therefore, even as we began research at the NCPTT project area of Santa Catalina Island, located about 31 kilometers to the north of San Clemente Island, we had already achieved a good deal of success in our efforts to find archaeological sites using commercially available SAR and multispectral data. We found that the image layers most useful to the wide area inventory of archaeological sites on San Clemente Island were those that were produced by XVV, XVV DEM, and NDVI data (discussed below).

Transferability of Protocols

Regarding the transferability of protocols developed for San Clemente Island to Santa Catalina Island, however, there were, and are, two important considerations. The first of these is that the environment at San Clemente Island is different in important ways from that of Santa Catalina. This will be discussed in more detail later in this report. For now, it is enough to say that topography is much more severe on Santa Catalina, and that vegetative cover is much heavier there. Severe topography complicates the geometry of radar backscatter, so much so that, as was suggested to us by interim results during this research, it seems likely that the accuracy of pixel values is compromised during the resampling that is a necessary step in the orthorectification of radar images. One solution was simply to consider only the portions of the landscape with slopes of less than 20 degrees. From an archaeological standpoint, this was acceptable because sites are virtually never found at slopes greater than 20 degrees, unless they are caves or rock shelters (for which we did not attempt to develop signatures in this research); or are cut through by ravines that were eroded after occupation of the site.

The other consideration is that, while X-band served us very well in our research at San Clemente Island by providing data that were used to produce both images and DEMs, these two products were less useful in developing certain materials associated with archaeological sites at both San Clemente Island and Santa Catalina Island because vegetative biomass was much greater at the latter. The X-band is about 3 centimeters in length. Unlike longer radar bands, it does not penetrate the materials it encounters much at all before it is scattered (see Fig. 2). What we have with an X-band DEM is a model of the surface exposed to the sky, which in most cases at Santa Catalina Island, is vegetation. Because of this, as will be discussed in more detail below, the DEM generated from X-band data provides us with a surface model that diverges from an earth surface, or "bald-earth," model considerably where vegetation is of a substantial height. Thus, the slope image layer that was used in archaeological site signature development did not, in some areas, truly reflect the slope of the ground surface, which is a factor that influenced site distribution in prehistoric times.

P-band, with a wave length of about 70 centimeters, penetrates materials much more readily than does X-band (or any of the other shorter SAR bands). The extent of penetration is greatly affected by water content, the greater, the less penetration. It has been demonstrated, nonetheless, that P-band can pass through the upper layers of rainforest canopy. For example, it has been used to image coffee and other crops that grow beneath these layers. Another factor that determines the extent to which P-band penetrates material is bandwidth, the larger, the more penetration. In order to avoid interference with television and citizen band radio, however, the P-Band must be "notched" to remove small sections of the bandwidth that correspond to these transmissions. While notching has been perfected by JPL radar engineers, effective notching protocols have yet to be put in place by the private sector. This is perhaps due to the fact that private sector SAR P-band data available to date have largely been collected in areas outside of the United States (e.g., in areas with tropical rainforests), where interference with television and citizen band radio is not an issue, and so notching is not necessary.

The P-band imagery generated from data collected by the private sector SAR platform for San Clemente Island was unusable because of the notching problem. In contrast, the P-band imagery generated from data collected by AIRSAR was usable, and it proved to be very useful as an image layer in developing archaeological site signatures for San Clemente Island. In the SERDP research, P-band was found to be not quite as useful as X-band imagery, but those results are closely tied to the specific environment on San Clemente Island. Because sites on San Clemente Island were covered only by grasses and small shrubs, which in many cases grew sparsely, X-band was scattered in a distinctive way not only by several species of grasses that provided a vegetative marker for archaeological sites there, but also by the scatter of fist-sized rocks that were present on virtually all habitation sites. The distinctive image layer signature developed with P-band backscatter was dependent upon quite a different phenomenology. In the case of P-band, it penetrated the relatively thin vegetation quite readily, and was reflected by the site soils beneath, which had a

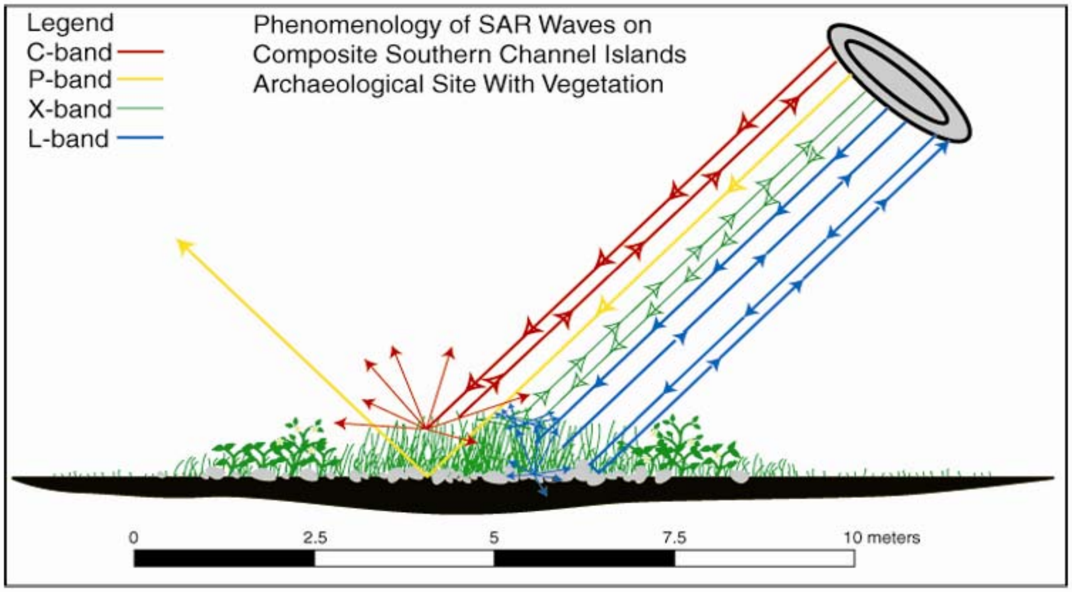


Fig. 2 Phenomenology of SAR waves at a southern Channel Islands archaeological site with composite characteristics

high dielectric property. That is, these soils conducted more readily than did surrounding soils. Since SAR is transmitted to the side, the effect was not unlike shining a flashlight on a mirror lying on the floor of a darkened room. The cone of light that falls on the sphere can be seen, but only faintly, because most of the light is reflected away from the viewer by means of the highly reflective surface of the mirror. Similarly, P-band returns from archaeological sites on San Clemente Island were characteristically less that returns from surrounding areas.

On Santa Catalina Island, as mentioned, vegetation is typically dense brush with numerous scrub trees and some large trees. X-band can not penetrate this type of vegetation, and therefore can not be used to find rock scatters associated with Gabrielino habitation sites. Also, the vegetative marker of grasses was not present at Santa Catalina sites, because other sorts of vegetation had overtaken them. Even so, X-band returns were statistically different from habitation sites. Therefore, it seems likely that there is a complex of vegetation on Santa Catalina, which may differ in precise plant types but that is structurally similar, which is more likely to grow on archaeological sites. Also, X-band did work remarkably well as an image layer in signatures for lithic scatters, probably because these tended to be on hilltops or ridge tops where soil development was minimal, so that the vegetative cover was correspondingly thin. Lithic debitage and the rare tool found at these sites are of a scale that scatters X-band.

Had the P-band data been of enough quality to have produced useable images, however, P-band data might have been used to develop a stronger image layer in the development of site signatures than did X-band data. This is because it could well have penetrated the thicker vegetation on Santa Catalina Island. From this data, we might have been able to produce a P-band image signature based upon the phenomenology of P-band SAR described above. Further, GeoSAR collects P-band data with dual transmitters and antennae, and therefore it is possible to analyze this data interferometrically. Doing so would produce a P-band DEM, or more properly, a DTM, as the surface model produced with P-band is usually quite similar to that of the terrain itself, denuded of vegetation and buildings. While z-values are somewhat less accurate than those in an X-band DEM (see Fig. 3, below), the P-band DTM, with an accuracy of would have better reflected the true slope of areas, and therefore have been the basis for an improved image layer signature from the SAR slope image layer (in this case, a P-band slope image layer). P-band images could also, in this case, have been used to develop an image layer signature based upon the weaker P-band returns from archaeological sites.

GeoSAR Interferometric System Parameters		
	X-Band	**P-Band**
DEM height accuracy	0.5-1.2 m (relative) 1-3 m (absolute)	1-3 m (relative) 2-5 m (absolute)
Planimetric accuracy (1 sigma)	2.5 m (absolute) 1 m (relative)	2 m @ 5 km altitude (absolute) 4 m @ 10 km altitude (absolute)
Ground swath width	20 km	20 km
Wavelength at center frequency	3 cm	86 cm
Bandwidth	80/160 MHz	80/160 MHz
Polarization	VV*	HH & HV or VV & VH*
Baseline length	2.6 m	20 m

*H=Horizontal; V=Vertical

Fig. 3 GeoSAR Interferometric System Parameters

It was not possible to arrange an AIRSAR data take for Santa Catalina Island, because the platform had been mothballed. However, as part of the program to ready GeoSAR for the private sector consortium that would take delivery of the final product, JPL arranged for testing data takes of Santa Catalina Island, and processed the data collected with their Jurassic Proc software. Thus, we were able to acquire multiple-flight line data that was processed in the way that our San Clemente SAR data had been.

Since that time (2004), GeoSAR has collected data for the entire state of California, and much of Florida. For most of the time, however, the platform has been pressed into almost continuous service by the federal government for reasons that have not been made public.

Custom-designed, multiple-flight line data takes such as those that JPL/NASA conducted or facilitated for us while AIRSAR was in operation and GeoSAR under development are optimal to archaeological survey. To an extent that is not easily determined, such flights might be difficult to arrange in the near future. There are few airborne SAR platforms, and special deployments to even large archaeological survey areas might not in the near future provide enough revenue to motivate private sector companies to provide them, unless survey areas fall in areas on the way to or from the large survey projects. Even then, careful planning and communication will be required in order to ensure that multiple flight lines are flown in optimal locations. Eventually, though, if a broad market develops for aerial SAR data products, archaeologists will have access to them. It is also possible as high-resolution SAR satellites go into orbit (e.g., the recently launched TerraSar and ALOS) that multiple data takes from these platforms could provide data sets useable to archaeologists.

In summary, the NCPTT grant enabled us to evaluate the contribution of both commercial SAR and commercial multi-spectral data sets in an environment different in important ways from that which was the study area for the SERDP research. Santa Catalina Island has much more topographic relief than does San Clemente Island, being a series of peaks and valleys rather than marine terraces. It is also different environmentally in other key ways, many of which are related to the fact that there is much more water on Santa Catalina Island than on San Clemente Island. Finally, the universe of archaeological sites is somewhat different on the two islands. More of the details of these differences, as well as their implications, will be discussed in the Results and Discussions section of this report.

Study Area Description

Santa Catalina Island is located at 33.3° N, 118.3°W, in the Southern California Bight. It is 33.7 kilometers long, and at its widest point is 11.7 kilometers. It is separated from the mainland by waters up to 880 meters in depth. It is, in fact, off the main continental shelf, occupying what is in effect a continental shelf of its own. At 32 kilometers from the Palos Verdes Peninsula on the mainland, it is slightly closer to San Clemente Island, which is 31 kilometers to the south. The Catalina Basin, between Santa Catalina and San Clemente Island, reaches depths of 1200m. Mountain ridges on Santa Catalina Island extend from northwest to southeast, with Mount Orizaba the highest point on one of them, 640m above sea level.

It is likely that Santa Catalina Island and San Clemente Island were occupied soon after humans reached the New World. From at least approximately 2,500 years before the present to the early nineteenth century, residents on both islands spoke the same Uto-Aztecan dialect, and have been considered by historians and anthropologists to have shared the same culture. For many years, they were commonly referred to as Gabrielinos; although today some members of this group prefer to be called Tongva. The Gabrielinos, or Tongva, also inhabited the lowlands along the seacoast in what are now southern and eastern Los Angeles and northern Orange Counties, as well as San Nicolas Island. While the Gabrielinos believe that they occupied Santa Catalina much earlier than 2,500 years before the present, conclusive material evidence of this has yet to be found. What is certain from recovery of datable human remains is that the island was occupied by about 10,000 years before the present. Further, occupation by humans at an earlier, and perhaps much earlier, time is likely. Ocean levels have risen steadily since the last glacial maximum (for example, approximately 300 feet over the last 12,000 years), and so it is possible that human groups that were exploiting the rich concentration of sea mammals and other sea life to be found along Channel Island coastlines left evidence of occupations that are now submerged.

Precipitation on Santa Catalina Island averages a little over 300 millimeters per year. In comparison, precipitation on San Clemente Island is about 150 millimeters per year on the northern portions of the island, although the central highlands receive about 300 millimeters. As mentioned, the presence of water is much more in evidence on Santa Catalina Island than on San Clemente Island. This is due not only to the greater overall precipitation on Santa Catalina, but also to the many steep canyons which concentrate precipitation that forms streams, which then water valleys down slope.

Previous Research

No synthetic treatment of the findings of archaeological research on Santa Catalina Island exists, although a proposal for this made in the 1970s by UCLA archaeologists was found at the Santa Catalina Island Museum. Most of the work conducted on the island by professional archaeologists was done by the University of California, Los Angeles (UCLA).

Before the first field session on Santa Catalina Island, we conducted a thorough search of all reports and documents pertinent to the archeology of the island. By the time of our first fieldwork session, we had obtained all site records and associated documents from the California State Archaeological Archives at the University of California, Fullerton, as well as those at the University of California, Los Angeles. Together these comprised what seems to be most of the written records that pertain to previous archaeological research at Santa Catalina Island. These included: site survey forms, attempts to consolidate information from survey forms on an archaeological base maps, reports written by avocational archaeologists in the early years of the twentieth century, research proposals prepared by professional archaeologists, site reports and other relatively lengthy but unpublished descriptions of findings at a number of large sites on the island, and reports on particular sites or types of artifacts done by undergraduate or graduate students. During our first field session, we also examined archaeological records at the Research Center of the Santa Catalina Island Conservancy, and copied those that were relevant to our research.

A good deal of field work--if the activities of avocational archaeologists, collectors, and professional archaeologists can be covered by this single term--has been done on Santa Catalina Island for more than 100 years. In examining the data obtained from Fullerton and that at the Research Center, we discovered that over 1,000 archeological sites have been recorded on Santa Catalina since about 1850. The most complete listing of activities related to archaeology is "A Bibliography of Catalina Island Investigations and Excavations, 1850-1980," by Robert J. Woldarski (1982). Decker (1969) reports on the collection of artifacts from Santa Catalina Island for museums, some of them in Europe, from 1857 onward. Santa Catalina Island attracted attention from serious archaeologists by early in the last quarter of the nineteenth century. With sponsorship by the Smithsonian Institution, Peabody Museums, and the United States National Museum, Paul Schumaker conducted surveys and excavations from 1875-1879. His work resulted in some of the few articles ever to be published on Santa Catalina Island archaeological research (Schumacher 1875, 1878, and 1879). Schumaker collected artifacts that reside in the sponsoring museums. Among the places from which he collected were sites at Little Harbor. A little over a decade later, Charles Frederick Holder, an "explorer" in the terms of the day, collected artifacts on Santa Catalina Island, including at Torqua Cave, Little Harbor, and the Isthmus. Holder penned several popular books and articles based on his adventures, which do not qualify as professional reports. Ralph Glidden also conducted surveys and excavations at Santa Catalina Island from 1915 to 1923. As reported by Wlodarski (1982: 8-10) he found 105 "campsites." He also excavated 316 burials, placing the most spectacular artifacts he discovered in museums, including his own Glidden Museum in Avalon. Although Glidden's activities were sponsored by the Museum of the American Indian and George Heye, for the sake of our present and future knowledge of Santa Catalina Island's prehistoric past it would have been better if he had not excavated and collected on the island, as the documentation he left behind of his activities and findings falls well short of today's standards for archaeological fieldwork. In the 1950s, C.W. Meighan, known by some as the 'Grand Old Man of California archeology,' was very active on the island. His 1953-1955 excavations at Little Harbor were the basis for a 1959 article in American Antiquity entitled, "The Little Harbor Site, Catalina Island: An Example of Ecological Interpretation in Archaeology." Remarkably, Meighan states at the beginning of this article that it is the "…first published site report for Catalina Island and the first complete description of a site excavation for the Channel Islands as a group" (Meighan, 1959: 383).

Meighan's analysis of food remains recovered from the Little Harbor excavation held enormous implications for understanding the special environment of the island, and the cultural adaptations made to that environment. As he said (Meighan, 1959: 400):

> Land animals available for food…appear to have been severely limited in number and kind. Catalina does have a species of deer, but from the animal bones in the Little Harbor site this could not have been of more than casual occurrence in the diet. Other land animals include ground squirrels and the small island fox. There are no rabbits. Such animals as cattle, pigs, goats, and bison, all of which are now present, represent Caucasian introduction and could have played no part in the Indian economy. Various species of marine birds and migratory waterfowl must have been available seasonally. However, the island has little marshy habitat to attract ducks and geese, and there is relatively limited evidence of bird utilization in the faunal remains from the site. Quail are abundant on the island today and were probably utilized aboriginally.
>
> There is no doubt that the major resources for the Little Harbor inhabitants did not come from the island itself, but rather from the marine resources along the shore line. Fish, shellfish, and sea mammals were the dietary staples.

Howard (1988: 6) summarizes Meighan's analysis of faunal remains as follows: "…81% Cetacea, 16% Pinnipedia, and 3% Carnivora and Artiodactyla bone, combined with fish and shellfish." The predominance of whale, dolphin, porpoise, seal, and sea lion in the diet of the prehistoric inhabitants of the island attest to the sophistication of prehistoric vessels, and a high level of seamanship. Additional evidence for this is provided by a re-analysis of the three southern most Channel Island faunal collections conducted by Judith F. Porcasi and Harumi Fujita, and published in American Antiquity in 2000, entitled, "The Dolphin Hunters: A Specialized Prehistoric Maritime Adaptation in the Southern California Channel Island and Baja California" (Porcasi and Fujita, 2000). The commitment to maritime resource exploitation that this indicates is consistent with the types of sites that have been recorded on San Clemente and Santa Catalina Islands, and also with the difference between site patterns on the two islands (see below).

Few full site excavation reports have been prepared since Meighan's, and of those that have been prepared, none that I could find in a professional archaeological journal. Further, while many surveys have been conducted, only preliminary or summary survey reports have been prepared. And of course, as mentioned previously, there has been no synthesis of the archaeological research on Santa Catalina Island.

The locations of the archaeological sites that have been recorded by survey forms have often been imprecise. In the majority of cases, locations of sites rediscovered during the field work done as a part of the NCPTT grant have been about 80 to 100 meters from those on sites forms. Site forms that were filled out by students participating in field schools are generally in error, and in many cases recorded sites that could not be relocated. This is especially so in regard to lithic scatters.

At least six different site numbering systems have been employed at Santa Catalina Island. A particularly valuable find at the Fullerton archives was an archaeological base map (on blueprint-sized paper) showing locations of sites numbered to correspond to site numbers on the site forms. (In some cases, forms were originally numbered using one of six different systems.) Unfortunately, there was no indication on the base map of who made it, nor was there any conclusive way to determine who had inserted corresponding numbers on the site forms. Also, the base map was undated. It seems very likely, nonetheless, that the base map and site form numbering was done at UCLA, as most of the site forms were filled out by UCLA personnel.

The Catalina Conservancy provided a GIS layer (shapefiles) of the locations of archaeological sites. Site numbers on this layer did not match those on the base map obtained at Fullerton. In order to determine the sites to which point shapefiles in the GIS layer referred, the base map obtained at Fullerton was scanned and georeferenced. Locations for particular archaeological sites as seen in the Conservancy GIS layer and as seen on the Fullerton base map were close enough in about 80% of cases to indicate strongly that the locations seen in the two documents were for the same site.

Site Types

For the purposes of this research, it was important to organize types of sites on Santa Catalina Island on a morphological basis. It is site morphology--broadly defined as including soil characteristics; the presence, size, and shape of lithic materials; topography (e.g., mounded or convex); species or complex of vegetation associated with site location; and position on slope--after all, that govern the return registered by a given sensing device.

From our field session and a survey of the literature, we divided all of the sites that we found during field work into five categories:

1. *Lithic Scatters*

The first type of site is the lithic scatter. Where found on Santa Catalina Island, these were on hill or ridge tops with sparse vegetation (because of poor soil development and removal of soil by aeolian action). They generally contained debitage with a few flakes that had been pressure flaked; an obvious core, or a tool, usually broken, perhaps during manufacture. These occur mostly in the interior of the island in places without a view of the ocean. Lithic sites on Santa Catalina Island are more obvious than those on San Clemente Island because of the relative abundance of lithic material that would obviously be suitable for making tools. On Santa Catalina Island, we see the results of initial reduction of cores, and perhaps less care in flint knapping. Flint knapping would have occurred on San Clemente Island in a much more studied and careful manner in order to extend the usefulness of a precious resource as much as possible.

2. *Habitation Sites*

The second kind of site looks very much like the typical habitation site one would find on San Clemente Island. These average about 10 meters in diameter and are marked by dark, carbonaceous, organic soils that include fragments of shell, and sometimes bone from sea mammals. On San Clemente Island, habitation sites typically do not display more than a flake or two of lithic material. Here on Santa Catalina Island, however, lithic debitage is much more common at habitation sites. This is probably because the white quartz and variolite, from which tools are made, both here and on San Clemente Island, come from Santa Catalina Island. So far we have found habitation sites with evident midden deposit only at locales with a good view of the water. I suspect that this is because habitations were placed both on San Clemente Island and here in locations where the movements of sea mammals could be observed. When, for example, pods of dolphins were seen, the word had to be spread quickly so that hunters could launch their canoes, surround the sea mammals, and herd them into shallows where they were killed.

3. *Stone Bowl Quarry Sites*

The third type of site is a quarry for the stone that was used to make bowls, effigies, beads, and something that functioned as a frying pan. On Santa Catalina Island, this stone is soapstone. Virginia Howard has done a survey of these sites on the island. She located more than 300 of them over a three year period, using crews of archeologists and volunteers from both the mainland and the island. On San Clemente Island, quarries were for basalt, especially nodules of basalt.

4. *Village Sites*

While there were concentrations of individual habitation in areas that were continuously occupied for thousands of years on San Clemente Island, there are sites that are indisputably villages on Santa Catalina Island. In fact, village sites have been found at all coves into which streams flow.

5. *Ceremonial Sites*

While this type of site most certainly exists on San Clemente Island, none have been recorded archaeologically on Santa Catalina, and we found no sites during our field sessions that obviously fell into this category. Ceremonial sites we found at San Clemente Island were the revitalization sites associated with the *Chinigchinich* cult. This ceremony in many ways resembles those associated with the Ghost Dance and Sun Dance of the Plains Indians. As with all revitalization movement ceremonies, the intent was to bring back the ancestors who would restore a way of life under threat. There are several historical and ethnographic accounts of the *Chinigchinich* cult at Santa Catalina Island, however (see, for example, Hardy, 2000: 85).

Methods and Materials

Remote Sensing Data Sets

This research utilized two remote sensing data sets, both of which were obtained commercially. The first of these was a SAR X-band data set, collected with the airborne, GeoSAR platform, owned by EarthData. From this, two image layers were derived. The first of these was an image generated from X-band backscatter, the second a digital elevation model (DEM), that is, a surface model made by the Interferometric analysis of X-band backscatter. The surface portrayed by the model was of whatever on the landscape was exposed to the sky. That is, it included not only exposed earth, but also vegetation and

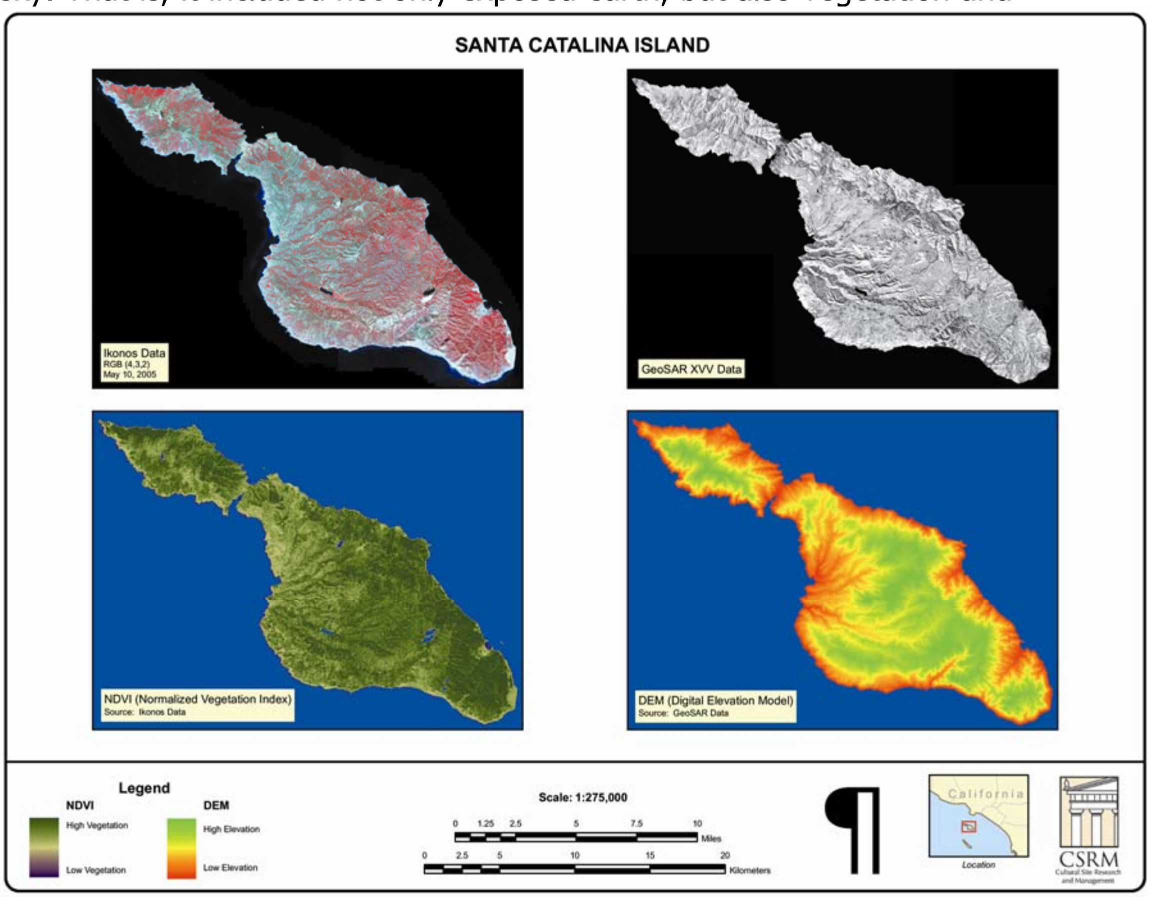


Fig. 4 Image layers used in the signature development analysis. Upper left: IKONOS image in false-infrared layer stack (reds indicate vigorous

vegetation). Lower left: NDVI analysis if IKONOS image (analytical statistics were run on this image). Upper right: the XVV image, created from XVV backscatter (analytical statistics were run on this image). Lower right: a digital elevation model (DEM) created through Interferometric analysis of XVV backscatter (analytical statistics were run on this image).

structures. This is because the X-band is very short (about 3 centimeters) and so is readily reflected by most materials (in general, the longer the radar band, the more penetration). The third image layer was the NDVI (normalized difference vegetative index), which was developed from four-band (red, green, blue, and near-infrared) IKONOS imagery. The IKONOS satellite was launched by Space Imaging and is now owned by GeoEye, Inc. The NDVI is generated by means of a standard algorithm that is frequently used in environmental studies to gauge vegetative vigor. Healthier vegetation reflects more near-infrared radiation that does less healthy vegetation, and is, in general, greener. NDVI values increase as near-infrared and green values rise, and as red values decrease.

SAR

Radar is an active remote sensing system that emits electromagnetic signals and then detects their return echo. In this sense, it differs from passive remote sensing systems, including common satellite images, which depend upon reflections of electromagnetic waves originating from natural sources. Synthetic Aperture Radar (SAR) is a well-established technology, although that has been steadily improved, designed to produce high resolution images of landscape features by collecting a series of radar echoes over a study area from a moving platform such as an airplane or satellite. The movement creates a synthetically large antenna that improves resolution. Topography, electrical permittivity, roughness, and geometry of the target affect radar echo. The response to physical, rather than purely visual, characteristics means that SAR has the capacity for identifying features not visible in optical imaging. Various SAR wavelengths can in most cases detect features obscured by clouds, dust, vegetation, and even soil. They can also be used to highlight patterns or anomalies of structure (e.g., vegetative structure, wave patterns, lithic structure or pattern) (See Comer and Blom, 2007a).

Some years ago, spaceborne radar was used to detect locations of forts along the Silk Route in the Taklamakan desert (Holcomb 1992) and for the acquisition of detailed images of sections of the Great Wall in China (Stover 1996: 21). Blom et al. (1984) and other scholars have demonstrated that radar images can help in the detection of ancient roads. The 1994 flight of the space shuttle Endeavor acquired images of Angkor Wat, Cambodia, with Space-borne Imaging Radar-C/X-band Synthetic Aperture Radar (SIR-C/X-SAR), revealing systems of ancient roads and canals (James 1995; JPL 2003a). Comer (1998) identified previously unrecorded structures and geomorphological features of importance to cultural history at Petra, Jordan, with data also collected in the 1994 Endeavor flight.

The analyses described above were dependent upon the "trained eye" of the image analyst. Areas that appeared anomalous to the image analysis expert, often because they presented the regular geometric pattern that is characteristic of humanly contrived changes to the landscape (e.g., architecture, fields, trails and other transportation systems), were marked as areas of interest that then required examination on the ground. The SERDP research produced a statistical means of automating the detection of humanly made features by developing signatures from sample areas were features of interest were known to be located, and comparing these with areas known not to contain such features(Comer and Blom 2007a). These protocols were the basis for those employed in the Santa Catalina Island research. Also among these were new protocols for orthorectification of images produced from SAR data that were developed by a team of JPL/NASA radar specialists under the direction of Ronald G. Blom of JPL/NASA (Comer and Blom 2007a). These produced precisely orthorectified SAR images (with distortion removed such that the scale is uniform in the output) by using DEMs developed from an interferometric analysis of SAR data. A version of these protocols is in use by the private sector company GeoSAR.

The statistical protocols initially developed in the SERDP research were used to analyze all data image layers. The first of these was the SAR X-band imagery, the second was a slope model generated by DEMs created from X-band SAR data (described just below), and the third an NDVI image produced from multispectral data collected by the IKONOS satellite (discussed below).

Slope Models from SAR DEMs As Signature Image Layers

As mentioned above, the DEM derived interferometrically from SAR data was used by the author not only for orthorectification of images, but also to create a slope model, which is an image layer to be analyzed in determining sites signatures. The GeoSAR platform collected X-band and P-band SAR data (as opposed to the C-, L-, and P-band data collected by AIRSAR). A comparison of these various radar bands is seen in Fig. 1.

An advantage of using X-band data for DEM production is that the DEMs so produced are more precise than those created from SAR bands of greater length (e.g., C-, L-, or P-band). This is a function of wave length. X-band is shorter than most others (and all of the others just given as examples). GeoSAR DEMs were used to generate a slope model with degree of slope being calculated for every 3-meter pixel within the AIRSAR DEM, in comparison with 5-meter pixels usually calculated for C-band DEMs. The GeoSAR DEM that was developed using X-band data as opposed to C-band data also provided greater height elevation accuracy—about 0.5 meters compared with about 1-meter. Because the GeoSAR X-band DEM was comprised of 3-meter pixels, slope could be determined every 3 meters, instead of every 5 meters as is the case with a C-band DEM. Bear in mind, however, that the X-band DEM provides a surface model not of the ground surface, but of all surfaces exposed to the sky. This includes vegetation and buildings. Thus, a DEM produced from P-band would be less precise, but would more accurately depict the surface of the earth itself. This would almost surely be preferable for the purpose of developing a slope image layer. Unfortunately, the P-band DEM could not be produced by the private sector vendor, for reasons given above.

Multi-spectral Data

IKONOS multispectral (four-band) imagery provided the basis for the third image layer that was used to determine site signatures in this study. The four IKONOS bands (Blue, Green, Red, and Near-Infrared) and corresponding wavelengths are as follows:

Blue: 445-516nm
Green: 506-595nm
Red: 632-698nm
NIR: 757-853nm

Relative spectral responsivity of IKONOS sensors to all wavelengths within the above ranges is not equal, as seen in Fig. 5.

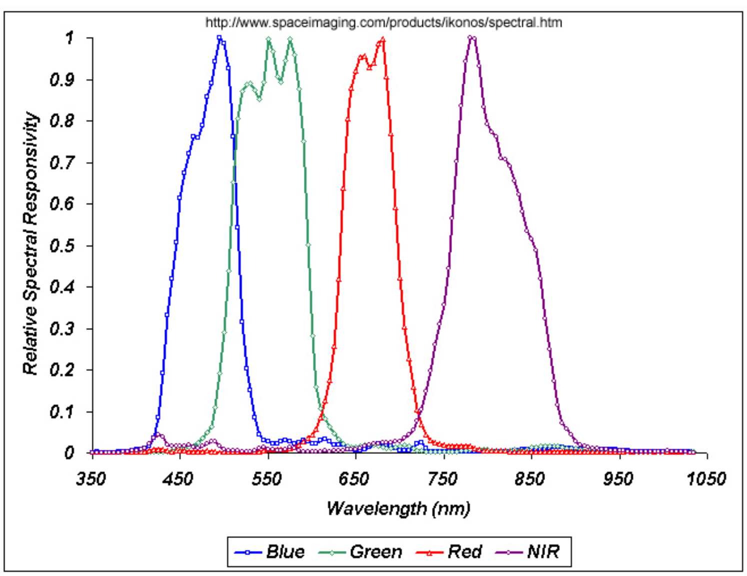


Fig. 5 Relative Spectral Responsivity by Each IKONOS sensor

The SERDP research by Comer and Blom at San Clemente Island established that the statistical protocols for signature development used for SAR image layers could also be used for image layers derived from multispectral data. In this study, they took into consideration both multi-band ASTER satellite imagery and IKONOS satellite imagery, after noting that certain of the known sites on San Clemente stood out clearly in images produced from both kinds of data. This was true:

1. When bands were stacked according to the convention for viewing the infrared band in conjunction with color bands;

2. When the Tasseled-Cap transformation for IKONOS (Horen, 2003) was utilized for enhancing the near-infrared effect; and

3. When the NDVI algorithm (NIR-Red/NIR+Red) was used with IKONOS data. In that study, the NDVI algorithm produced the multispectral image layer judged most useful in developing signatures for archaeological sites on Santa Catalina Island. For that reason, the NDVI imagery was used in developing archaeological site signatures on Santa Catalina Island.

GIS Layers

GIS layers obtained from the Conservancy were very useful, including layers for roads and island boundaries. Of special importance was the IKONOS imagery provided by the Conservancy, which was donated by GeoEye (then, Digital Globe) through the efforts of Prof. Glen Gustafson, a volunteer at the Conservancy. Digitized USGA maps were obtained from files at CSRM. What follows is a listing of the GIS layers we worked with in this research. All were assembled in a Geodatabase (which we will send to the Conservancy):

<u>VECTOR DATA</u>
Archaeological sites
Contours
Geology
Hydrography
Ponds
Soil
Island Polygon
Viewshed zones
Roads
Observation points used to establish viewshed zones
CSRM surveyed areas and recorded sites

<u>RASTER DATA</u>
X-band DEM and image
NDVI
Scanned USGS maps

AIRSAR
LIDAR
IKONOS image

<u>TIN DATA</u>
Tin DEM

Field Investigations
Following the thorough archival research described earlier, the author conducted three field sessions: the first was from 11 August 2005 through 19 August 2005; the second from 26 December through 30 December 2005, and the third from 9 August through 14 August 2006. Field work benefited from approximately 640 hours provided by volunteers. Volunteers included Margaret Beck, Matt Hill, and Christopher Purcell, from the Cotsen Institute of Archaeology; Desiree Martinez, a Ph.D. Student at Harvard University, and member of the Gabrielino tribe; Collin O'Neill, an archaeologist with five years of experience in southern California archaeology; Douglas McFadden, archaeologist with 30 years of experience in the Southwest, formerly of the BLM, now Principal of McFadden Archeological Consulting; Jacob Comer and Lange Auman from Gilman School, in Baltimore, Maryland; Margaret Comer, from Bryn Mawr School in Baltimore, Maryland; and Elizabeth Comer, Principal of EAC/A, Inc. Additional fieldwork was conducted in September of 2007 by a field school organized by Douglas Comer, Desiree Martinez, and Dr. Wendy Teeter (Curator of Archaeology, Fowler Museum at UCLA) through the Cotsen Institute and in collaboration with the Santa Catalina Island Conservancy. The survey utilized field equipment under development by the US Army Corps of Engineers Construction Engineering Research Laboratory (CERL) through a Cooperative Research and Development Agreement (CRADA) with Cultural Site Research and Management (CSRM). This equipment records GPS locations from a distance, while also recording supplemental environmental data (elevation, time, temperature), and obtaining a color, digital image of the site and an infrared image of the site. The results from this survey, however, were not available in time to be used for this report. The results will be utilized in future remote sensing research on Santa Catalina Island.

Results and Discussion

Protocol 1: SAR Data Collection: Look Angle, Mode, and Optimal Flight Lines

Look Angles and Flight Lines
Optimal data collection is accomplished by means of *complementary look angles.* All SAR platforms illuminate the area to be examined by means of transmitting electromagnetic waves of microwave length. Only planes facing in the direction of the transmission are illuminated and subsequently sensed, with other surfaces remaining undetected and thus not subject to characterization until illuminated from the proper angle. Complementary look angles are produced by executing

flight lines from different sides of the area to be examined. Ideally, this would be done by illuminating the same area from the north, south, east, and west. Depending upon topography, however, only two or three angles might be required, or four might not be enough. The topography of Santa Catalina Island, however, is both complex and severe. Therefore, SAR data should be collected from at least four flight lines to provide illumination from four angles separated by 90 degrees.

Choice of Band and Polarization
The most informative radar band polarization will depend upon the characteristics of the sites to be found, especially structural and chemical, and the general environment of the area to be examined. At San Clemente Island, for example, we saw, during the SERDP research of 2002-2005, strong evidence that both C- and L-bands interacted with the rock scatters associated with the presence of archaeological sites. They seemed also to be reflected by grasses and brushes that grew in profusion anomalous to surrounding vegetation.

The available private-sector aerial SAR platforms, however, carry, at most, only P- and X-band (See Fig. 1). In the case of GeoSAR, P-band can be polarized in two ways, as compared with AIRSAR's four, and X-band is polarized only VV.

As noted above, X-band does not penetrate materials of any sort to any appreciable extent. It is scattered by almost any small structure. This includes, fortunately, the structure of vegetation.   Soils created by human occupation can be expected to be richly organic, ashy, and to contain rock, stones, shells, and artifacts. They almost always, therefore, attract distinctive sorts of plants, which frequently grow more thickly and with more vigor than do those surrounding them. This would seem to explain why X-band radar returns from even archaeological sites covered with vegetation on Santa Catalina Island are statistically different than such returns from the surrounding landscape. X-band, then, has been demonstrated to work well as a signature image layer in the environment of Santa Catalina Island. By extension, one would expect it to work well in similar environments.

As explained above, P-band collected by private sector SAR data vendors has proven to be of no value in the wide-area archaeological survey at Santa Catalina, and also in the SERDP investigation that had San Clemente Island as its test area. This is because imprecise "notching" of P-band bandwidth rendered the resulting P-band backscatter insufficient to generate a cohesive image.

In contrast, and on a more promising note, AIRSAR P-band collected by the JPL/NASA platform proved to be a very effective image layer in the development of archaeological site signatures. This is because of the soils that are created during human occupation. Such soils tend to clump, creating interstices that fill with water. Interstices between material introduced by human occupation (e.g., rock, shells artifacts) also fill with water. Water soaked soils are highly conductive to electricity. Because soils associated with archaeological sites are richer in organic materials than surrounding soils, they are also moister. Soil particles at archaeological sites tend to clump, producing interstices in which water is trapped. This, and perhaps the carbon in the soils from campfires, affects dielectric property, rendering the soil very conductive to electricity. The results of soil conductivity tests at archaeological sites at the old airfield on San Clemente Island established this quite well. These tests, conducted by Larry Conyers (2000), showed that all sites tested were enormously conductive. This conductivity would affect the propagation of radar waves much as a mirror affects propagation of light waves. Since radar waves are transmitted at an angle, longer waves would pass through covering vegetation to be reflected obliquely into space via specular reflection and not back to the radar platform. This is analogous to light from a flashlight striking a mirror obliquely. In both cases, the return from the area illuminated by the beam might be discernable, but would at best be weak, as seen in Figure 2.

Signature development for archaeological sites, approached scientifically, demands some prior knowledge of site morphology. As is true in general, we must know something about what we are looking for before we can hope to find it. The more known about the physical and chemical attributes that comprise the site, the better. Therefore, background research that either draws from prior fieldwork or collects information about site morphology by means of preliminary fieldwork is essential to the methods that are developed in this paper: the typical sorts of archeological sites must be determined in order to provide the universe of values from which signatures are created (see **Site Types**, above).The radar bands used should be selected on the basis of what is known prior to the investigation about the characteristics of archaeological sites in the inventory area. As to mode of polarization, structures that are marginally detectable because of their spatial orientation by bands of a certain wavelength are generally more detectable in cross-polar mode. Current private sector SAR platforms do not have cross-polar capability (as AIRSAR did), but we can hope that one might have it in the future.

While the shorter wavelengths proved to be most valuable in directly detecting archaeological sites at Santa Catalina Island, this will not be the case in every environment. In other areas, sites are to be found beneath soils or under forest canopy. For example, through an NSF grant, AIRSAR was deployed to Central America to find masonry features (expectedly Mayan) located beneath a tropical rain forest canopy. In this case, it is possible that un-notched P-band polarized to be transmitted and received vertically and transmitted at 40 MHz (more than permitted in most areas of the United States) will prove most useful (Comer et al., 2005). It is interesting to note, however, that preliminary findings are that the shorted SAR bands (C- and L-bands here) are producing anomalous returns that are likely produced by unusual vegetation type or growth at archaeological sites, even in this area having as dense a vegetative cover as anywhere on earth.

Protocol 2: SAR Data Processing and Image Production

Orthorectification

In order to fully exploit the capabilities of SAR to detect archaeological sites, images must be rigorously orthorectified. Before the SERDP sponsored project in 2002-2005, research utilizing radar imagery had been focused on very large features, often long and linear, or on areas that were generally homogenous in regard to broad taxonomic categories of interest, for example broad agricultural areas, geomorphologic zones, large ice sheets, and oceanic wave patterns (e.g., Moghaddam, M, 2001; Schmullius and Evans, 1997; Durden, et. al., 1989; Crippen and Blom, 2000; Gabriel, et al., 2000). To find relatively small archaeological sites, a much greater degree of precision was necessary. Sites on Santa Catalina Island can be tens of meters in diameter, but can be as small as only a few meters in diameter. Because most remote sensing imagery is made up of 5-meter square pixels, it is obvious that spatial accuracy is important. (The statistical approach described later makes the use of relatively large pixels feasible.)

Merging Data from Multiple Flight Lines

It was necessary that radar imagery be available for all locations within the survey area. To accomplish merging of data from multiple flight lines, JPL radar engineers developed what they dubbed "Jurassic Proc" software (for the gigantic body of data used and the enormous processing power required to produce images) to merge data from two or more flight lines. Interferometric data merged in this way provided a DEM of the area that is much more accurate than any produced before. At tests conducted on San Clemente Island, the images orthorectified by means of the interferometric digital elevation model proved to be amazingly accurate. For all of the radar bands utilized by AIRSAR (P, L, and C), an accuracy on the order of 5 meters was obtained. Ground control points for this test were supplied by a chicken-wire square that had been utilized by San Clemente Island botanists on contract with the U.S. Navy to protect indigenous plants being cultivated for habitat restoration from foraging animals; and a figure-eight arrangement of barbed wire left over from Marine maneuvers in the area of the island's old airfield.

Protocol 3: SAR Image Analysis (Post-Processing)

Iteration of Image Analysis

Analysis of all images and image layers developed for our Santa Catalina Island research was conducted numerous times, as described below. Results were compared with the universe of sites of a type from which the sample used in signature development was drawn. From a purely statistical standpoint, these were always quite good. From a practical standpoint, however, they seemed to portend difficulties for future, practical application in research and cultural resource management. This is because there were many isolated signatures, scattered over large areas that we knew contained slopes of over 20%. Given the difficulty inherent in orthorectification of radar imagery, and the fact that orthorectification is made more difficult by the sort of severe relief that is characteristic of Santa Catalina Island, we thought it possible that these scattered isolated signatures in areas where they should not have been generated were a manifestation of radar "speckle" Speckle is an artifact of rendering radar data to imagery; locations where backscatter has interacted at random to produce artificially high returns in some pixels. The phenomenon is somewhat like that of a "rogue wave" on the ocean, which is formed when two or more waves coming from different directions happen to meet in a way that combines the energy among them. Such speckling would affect two of our three image layers. For that reason, we trimmed our area of analysis to areas with less than 20% slope.

Quantitative and Replicable Analysis Methods: Statistical Techniques of Value in Establishing Signatures for Archaeological Sites

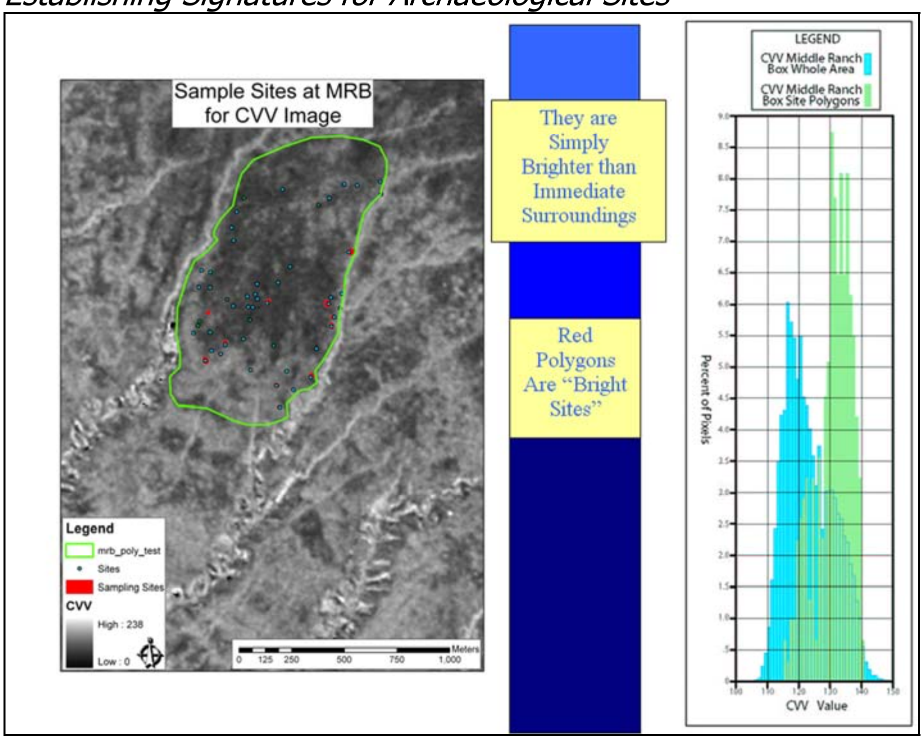


Fig. 6 Separation of CVV returns from archaeological sites compared with an equal number of areas of equal size randomly selected from the Middle Ranch Box sampling region at San Clemente Island

Our SERDP research at San Clemente Island culminated most notably with the creation of three products: 1) Standardized protocols for the use of SAR in wide-area archaeological site detection. For reasons laid out in the introduction to this paper, those protocols were widened a bit to accommodate the inclusions of other source of remote sensing data. These basic protocols are followed here, and are modified to the situation on Santa Catalina Island.; 2) The "Jurassic Proc" software that was developed as a means not only to merge data from several SAR platform flight lines, but also to orthorectify the images so produced. Until the SERDP sponsored research, this kind of precise orthorectification had not been identified as an engineering requirement; and 3) Statistical protocols that developed signatures from all image layers, including those developed from SAR data, but also those from multispectral data. This product was developed because the standardized signature development functionalities in existing image analysis and enhancement software were not as productive as we wished. Therefore, we developed our own grid algebra approach, initially employing this functionality in ArcGIS. We found that this also worked well with other data sets.

These grid algebra protocols provided the quantitative and replicable analytical method that we were attempting to develop. They are a replacement for the "trained eye" approach, which is not replicable, because it is fundamentally subjective. Rather than go through the proof that we presented for these statistical protocols in our SERDP report (which is the basis for a chapter by Comer and Blom in *Remote Sensing in Archaeology*, 2007), we will simply outline the approach here.

Our initial attempts at image analysis (sometimes called "image post-processing") were intended to make archaeological sites more visible in imagery. The first field session in which ground-truthing was conducted revealed, for example, that archaeological sites in certain areas were extremely visible as bright locations in the black-and-white C-band imagery. Having been thus encouraged to examine imagery, we developed ways to amplify the bright returns that were associated with archaeological sites, not only in the C-band imagery but also what we saw in the L-band imagery. We felt that we were quite successful in enhancing imagery so that sites could be identified through examination by trained observers. This, however, was only intuitive. We therefore began to look carefully at the range of pixel values generate by archaeological sites. The simplest form that this examination took can be seen in Fig. 6. In the two return histograms, one for those from archaeological sites in a sampling area at San Clemente Island known as Middle Ranch Box and the other from an equal number of randomly selected areas of equal size, we see that the two sets of returns form distinct distribution curves. In this illustration, though, we can also see that the immediate area in which the sites were found is simply seen as being quite dark in comparison with the overall landscape. Therefore, the generally higher returns from archaeological sites in Middle Ranch Box stand out especially well. More formal statistical analyses established that returns from archaeological sites found all over the island were, in fact, distinctive, as suggested by the histograms in Fig. 6, but that they could be either brighter or darker than immediate surroundings.

Knowing this, it was then a matter of running statistical analyses iteratively, interspersed with field observation sessions, until we identified the types of sites and environmental zones that were used in final signature development. To do that successfully required a thorough knowledge of archaeological site morphology and some grasp of the phenomenology of the radar waves and multispectral radiation with which we dealt.

Statistical Analysis vs. Statistical Description

The term "signature" is widely used by those who practice remote sensing, and is generally understood to refer to the characteristics of a material as discerned in remotely sensed data[2]. Images are merely one form in which data can be presented, a "graphical user interface," if you will. Images are important, however, because they are inherently spatial, that is, they provide the location of the material sensed. Nonetheless, a signature is often empirically demonstrated more clearly in other ways. Paramount among these are spectral signatures, seen in spectral response curves. A familiar response curve is seen below. The graph on the left represents a sample response of an unspecified material to solar radiation, which ranges from the visible to shortwave infrared.

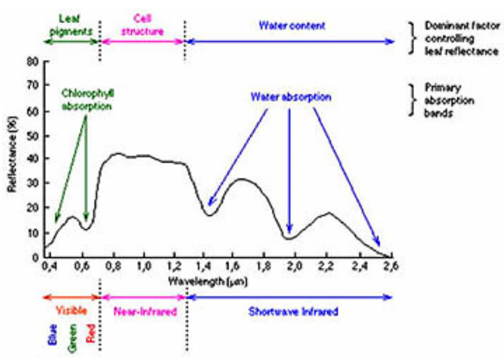


Fig. 7 Sample response of unspecified material to solar radiation

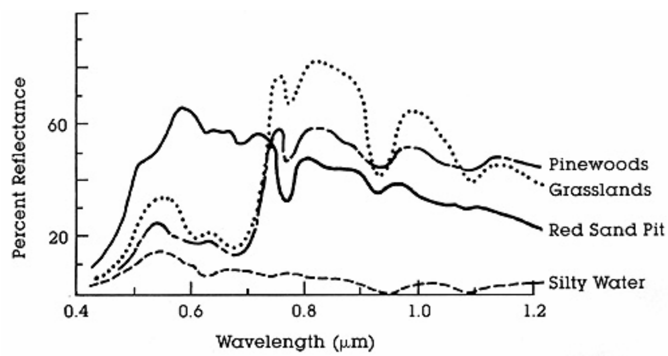


Fig. 8 Spectral signatures for different materials compared

The one on the right shows how such graphs can provide a visual model for differentiation among materials. Such a graph, of course, can also be represented mathematically. Typically, this is done with a statistical model, or description, of frequency distribution patterns. This leaves undone, however, the task of formally differentiating patterns associated with different materials. At this point, then, one can say that the statistics involved are only descriptive. A dictionary of signatures for different materials is often compiled by users of

2 The discussion that follows draws from NASA's online tutorial on remote sensing (http://rst.gsfc.nasa.gov/Front/tofc.html).

certain multispectral or hyperspectral sensing platforms (e.g., ASTER, IKONOS). To use these signatures in detecting materials, a normative approach is taken. That is, when signatures are observed that are similar to those in the dictionary, the possibility is raised that the material might be that in the dictionary.

With SAR data, characterization of material based upon graphing returns is not possible because the SAR sensing devices, being active, record only a single return (backscatter, in the case of radar) value for the discreet subset of the electromagnetic spectrum transmitted. This is in contrast to passive sensing devices, which, again, record responses to a wide, continuous range of the electromagnetic spectrum that is supplied by the sun. Even the most versatile radar devices transmit only two or three discreet bands.

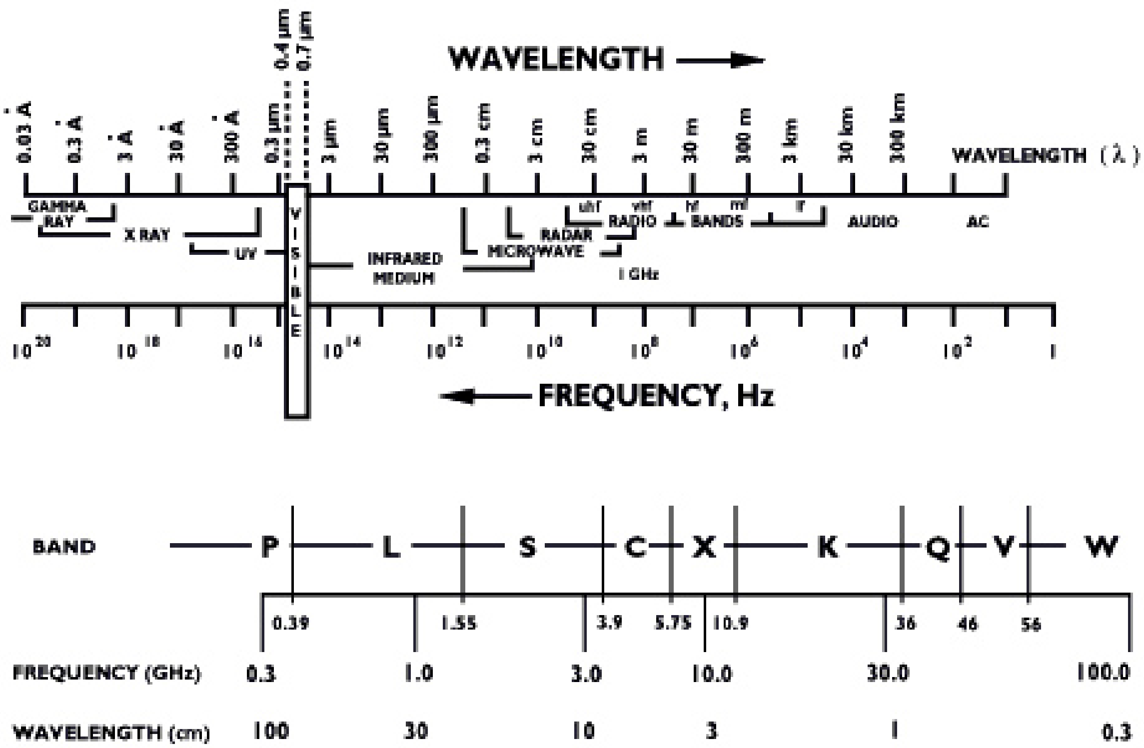


Fig. 9 Wavelength and frequency for various electromagnetic waves, including visible light and radar

Thus, the problem arises: how to differentiate response under these circumstances? The solution as developed during the SERDP research was simply to utilize analytical statistics to accomplish this task. Many statistical protocols could be used for this purpose, so long as they highlight the differences between returns from the material in question and the surrounding area. Experience has established to the satisfaction of the researchers that the best solution is the one that is the most elegant, that is, the least complicated statistical protocol that will accomplish the goal in mind. The essential task here was considered to be best and most simply accomplished by the *difference of means* statistical procedure. A number of other statistical procedures, including analysis of variance (ANOVA) might have been used, and under certain circumstances might be used if, for example, signatures could be improved by knowing the relative extent to which image layers contribute to differentiation of a site from the rest of the sensed area. Nonetheless, any such elaboration of statistical procedure carries with it a potential source of error. Therefore, only the simplest statistical procedure adequate to the task at hand was employed here.

Statistically, it is a straightforward exercise (although one having numerous steps) to determine whether or not signal returns from archaeological sites are different enough from returns from the rest of the survey area to conclude, within determinable probability parameters, that the values were taken from two different populations. To do this, again, we used a variation of a difference in means test. This test was carried out in two steps. The first step was to determine if, simply, there was enough difference between values obtained from the pixels within established archaeological site boundaries and values representative of all pixels not within archaeological site boundaries to justify the conclusion that the two sets of samples actually represented two different populations. The second step was to determine *which pixel values* were most strongly associated with the set taken from archaeological sites. That is, which pixel values were statistically different enough to justify the assertion that they were obtained from a population distinctly different from the rest of the island?

Steps 1 and 2 were both carried out using pixel values obtained from images at locations within archaeological sites and at an equal number of areas of equal size randomly selected from areas outside of archaeological sites. To do this, a circle was established utilizing the center point of archaeological sites that had been established to less than 1-meter accuracy. Around this center point was drawn a circle with a radius of 15 meters. Most sites recorded by our survey crews on Santa Catalina were at least 10 meters in diameter, but landscape differences (soils, vegetation cover, scatters of rock) sometime attenuated slowly outside the perimeter of the site. The essential rationale for this method was that it was most essential to reliably capture areas that were within site boundaries. The method allowed for a certain degree of spatial error. While this admitted the possibility that some areas unrelated to the site would be included in the sample, the statistical nature of the image analysis methods developed from this research could admit of such dilution of the essential data. Therefore, values were harvested from each of the pixels within sampling polygons. For the control sample, the universe of values known to lie outside archaeological sites, other 15-meter radius circles were established at randomly selected points outside of archaeological sites on the landscape. The statistical tests were then conducted utilizing values associated with these two sets of polygons.

Both steps 1 and 2 utilized the following statistical method:

Our null hypothesis was that there is no difference between the population of values that lies within site boundaries and the population of values that lies outside site boundaries, that is:

$$H0: u^1 = u^2$$

This was equivalent to testing the hypothesis that the mean of x1–x2 is 0. If the null hypothesis were upheld, of course, it would mean that pixel values associated with archaeological sites could not contribute to signatures for those sites. If, on the other hand, the null hypothesis were disproven, pixel values associated with sites could be used to develop signatures for those sites.

We tested this with the formula:

$$(\sum_{n}^{1} x^1 / n) - \sum_{n}^{1} x^2 / n) < 1.96 \sqrt{\sigma_1{}^2 / n + \sigma_2{}^2 / n}$$

Which is to say that the difference of the means of the site and randomly selected samples, or $(\sum_{n}^{1} x^1 / n)-(\sum_{n}^{1} x^2 / n)$, will be less than 1.96 standard deviations apart, with the standard deviation of the difference of means being determined by the elementary formula:

$\sigma_{x1} -_{x2} = \sqrt{\sigma_1{}^2 / n + \sigma_2{}^2 / n}$ (See, for example, Hoel, 1971: 172).

<u>NB: 1.96 is the cut-off value for a 95% degree of probability that two samples are drawn from different populations when sample size approaches infinity. The cut off value for smaller sample sizes will vary; e.g., for 20 samples it will be 2.086, for 15 it will be 2.131. We obtained very useful results with a sample size of 15.</u>

Optimal Use of SAR Bands, Polarizations, and Combinations of These

Step 1 results for San Clemente Island data indicated in a statistically valid way that, for all image layers tested, values within and outside of site boundaries were drawn from different populations. The optimal SAR bands and polarizations, as well as image layers developed from multispectral data sets, were assumed to be those for which the greatest number of standard deviations separated pixel values within known sites from pixel values within randomly selected areas of the same size and number. For San Clemente Island, among image layers derived from commercial data sets, these were XVV, slope from XVV DEM, and NDVI from IKONOS multispectral data. As these data sets could be obtained for Santa Catalina Island, they were selected for the Step 2 analysis there.

The Step 2 statistical analysis utilized the same formula, but it compared the means of all *individual pixel values* within archaeological site polygons with the means of all individual pixel values within an equal number of randomly selected polygons of equal size. These would be the same if the populations from which values were drawn (i.e., site and random) affected returns in the same way and to the same degree. That is, the null hypothesis in this case would be upheld. The pixels for which the null hypothesis was not upheld would be those that are associated with archaeological sites.

Protocol 4: Corroborative Use of Multispectral Data Sets
While radar image values were greatly influenced by vegetation structure and dielectric properties, multispectral imagery highlighted spectral attributes of vegetation, including those associated with vegetative health. NDVI (normalized difference vegetative index) values were used to locate the greener and more vigorous vegetation that developed at Santa Catalina Island archaeological sites (and is often at non-structural archaeological sites everywhere) by virtue of the enriched, organic soils produced by human occupation.

Taken together, then, radar and multispectral imagery were used to sense the following differences (as schematically depicted in Figures 6 and Figure 9).

1. *Topographic roughness at lithic sites, produced by clustered lithic debitage (sensed by SAR X-band)*: Given radar wave phenomenology, we can postulate that the X-band is strongly affected by surface roughness of this sort. X-band waves are roughly 3 cm in length. Features that are as small as one-fourth the length of the radar band affect radar waves. This is a dimension that fits with the size of debitage. Vegetative cover at lithic sites, unlike that at habitation or other types of sites, is very thin, which provides access to debitage by X-band waves.

While there are many factors which influence radar backscatter, the Rayleigh scattering criterion is a guide to radar backscattering behavior due to surface roughness (Peake and Oliver, 1971; Schaber, et. al., 1976). Surfaces become rough enough to begin backscattering significant radar energy at approximately 1/4 of the imaging wavelength. Surfaces smoother than this will be dark in radar images, surfaces rougher than this will be increasingly bright. Other key factors include imaging geometry, dielectric constant (largely a function of moisture content), and surface slope.

2. *Vegetative structures associated with archaeological sites (sensed by SAR X-band)*: Vegetation growing on an archaeological site is frequently of a different type than vegetation surrounding it because of soils enriched during human occupation of the site, as well as the presence of rock, shell, and other materials that alter soil moisture and chemical composition. It might be that thicker vegetation mass, made up of many individual reflective planes, provides a more effective scattering or reflecting surface than does thinner, and thus backscatter

from archaeological sites tends to be of a different magnitude than backscatter from other areas.

3. *Certain slopes are more conducive to human occupation and use than others (send by SAR X-band DEM)*: A slope value is associated with each pixel in a SAR DEM, just as a return value is associated with every pixel in a SER image or a multispectral image. Thus, the DEM can be statistically analyzed in the same way using the Step 1 and Step 2 protocols outlined above. In this case, pixel values found to be statistically different at archaeological sites are used as an image layer in signature generation.

4. *Vegetative vigor (sensed by multispectral data and perhaps by X-band SAR)*: As previously mentioned, archaeological soils are conducive to thick and vigorous vegetation. Such greenness and vigor are readily discernible by examination and analysis of NDVI images produced from multispectral data using a standard algorithm.

Protocol 5: Procedures for Incorporation into, and Analysis with, GIS
The means by which orthorectification of SAR images and multispectral images was done with the use of the SAR X-band DEM was described under **Protocol 2**, above. This, of course, was an essential step in the incorporation of these images into the GIS. Similarly, the statistical protocol that was employed through the use of the grid algebra functionality in ESRI ArcGIS was explained under **Protocol 3**. We have recently transformed these protocols into software that does not run within ArcGIS, although this development, which was funded by CSRM, is too recent to be reported fully here.

The final step in the development of site signatures was done for the images displayed in this report by merging image layer signatures with GIS. A simple Boolean procedure is executed for this using a raster calculator, such as the one standard in ESRI ArcGIS. Raster images are created that show site signatures for each image layer. In these raster images, each pixel comprising a 95% probability signature is assigned a value of 1, and each pixel outside a signature is assigned a value of 0. Then, the images are merged, and totals are calculated for each pixel. In the resulting raster image, pixels having value of 1 are those for which site signatures were developed from any one of the image layers; those with a value of 2 are locations where any two image layer signatures overlap, and pixels with a value of 3 signify locations where all signatures are indicated by all three image layers. We are utilizing a color convention in which pixels with a value of 1 are assigned yellow, pixels with a value of 2 are colored light green, pixels with a value of 3 are seen as dark green, and pixels with a value of 0 are made red.

Protocol 6: Procedures for Ground Verification of Site Signatures

Our method for ground truthing is to establish the center point for as many archaeological sites as possible per geomorphological zone into which the total survey area has been divided. Such points are established to an accuracy of less than one meter. From these sites, 15 are randomly selected to provide the sample pixel values with which to develop image layer signatures. From these image layer signatures the final, merged image layer signature for that type of site in that zone are generated. The total number of sites is used to test the veracity of the signatures.

If reliable ground control points (GCPs) have been collected previously, these can be used. If there is some doubt, GCPs can be verified, or new GCPs for site locations can be collected. During our fieldwork at Santa Catalina Island, locations of the archaeological sites that we found or rediscovered were about 80 to 100 meters from the locations recorded on site forms. The same can be said of the accuracy of the archaeological base map that was produced using the information on the site forms, and of the GIS shapefile layer provided us by the Conservancy. Adding to the uncertainty about site location was that six different site numbering systems have been employed at Santa Catalina Island. Therefore, we could only be sure of the locations of sites for which we actually took ground control points of one meter or less accuracy with our GPS units. Due to the extremely rugged terrain on Santa Catalina Island, we found only 37 habitation sites, 44 lithic sites, and 13 soapstone quarry sites. We did not attempt to develop signatures for village sites, as all of the places where villages were located have been greatly altered by modern development (e.g., Boy and Girl Scout camps, schools, research facilities, camp grounds, yacht basins, and the towns of Two Harbors and Avalon). No ceremonial sites could be identified, although some are known to have been located in village sites. We did not include site signatures developed for soapstone quarries in this report, either, because the sample size for signature was minimal, and the sample size for testing signatures was insufficient.

Conclusions

Signature establishment depends upon all protocols previously described. To summarize, the *statistically based site signatures* that we developed are predicated upon quantitative differences in the sensing device returns from archaeological sites that are statistically compared to returns from areas not within archaeological sites. This research has developed a way to establish archaeological site signatures using return values from as few as 15 archaeological sites within a given environmental zone. A statistical analysis method developed during this research was carried out for each site and nonsite pixel value for each image layer. Signatures were formed by pixel values that were at least two standard deviations away from the null hypothesis mean for pixel values taken from image layer images for areas within two sets of polygons, the first describing archaeological sites, and the second around randomly selected areas not within known archaeological sites. When the null hypothesis is disproven, we can be 95% sure that these two sets of pixels were drawn from different populations. The simplest, and therefore most likely, explanation for the difference of these special sets is that archaeological site characteristics are affecting return values. That assumption can be tested by comparing the number of sites that one would expect to fall within signature areas if they were randomly distributed with the number of sites that were observed to fall within signature areas.

The protocols that have been presented here enabled us to develop statistically-based signatures. This means that that if one goes to a signature locale, one can expect to a measurable degree of probability that the location is more like the archaeological sites sampled in terms of the image layer return in question than it is to non-site locations on the island. It is a fact, then, that signature areas will contain locations that are like archaeological sites in terms of the characteristics that were measured by the SAR and multispectral image layers that were used in the analysis, but are not archaeological sites. However, in terms of management of cultural resources, it is more important that the areas that fall outside signature areas are *unlike* archaeological sites in terms of the characteristics that are measured by the SAR and multispectral image layers that were used in the analysis. Therefore, it is more likely that some of the signature areas do not contain archaeological sites than that non-signature areas do contain archaeological sites. Therefore, when developments are planned, it will be beneficial to place them in non-signature areas where sites are much less likely to be found. By avoiding sites, one not only preserves them, but also eliminates the time and expense associated with an evaluation of the site for National Register significance, as well as the time and expense associated with site mitigation if it is found to be eligible for listing on the National Register.

The X-Band Image Problem
As mentioned, two image layers derived from X-band data collected by the GeoSAR platform over Catalina Island were utilized here. These were: the image generated by means of X-band backscatter (seen in the upper right hand corner of Fig. 4), and a DEM that was produced by Interferometric analysis of X-band backscatter (seen in the lower right hand corner of Fig. 4). The images were produced by research personnel in the case of SAR data collected by AIRSAR over San Clemente Island. However, the data products from GeoSAR had been pre-processed. That is, GeoSAR data had already been made into a DEM and an image before it was made available to us, and to the general public. The XVV image that was provided to us, unfortunately, has already been scaled, which is to say that the original backscatter values typically range from 0 (which indicates that no energy is transmitted back from the target) to about 1.4. The uppermost value should theoretically be 1, which would indicate that all of the energy transmitted to the target was returned. Values slightly above 1 are

accepted as being valid, however, even though it is obvious that "speckling," or perhaps the "rogue wave" phenomenon, plays a role in creating values over 1. These values are used to dictate the degree of shading assigned to each pixel, which is limited to 256 shades: 0 being white, and 255 being black, with all other shades falling in between. However, original returns are logarithmic, so higher returns are in reality enormously higher than lower returns. We discovered that, because of this, the manner in which magnitude is scaled to the shading values can affect signature development tremendously.

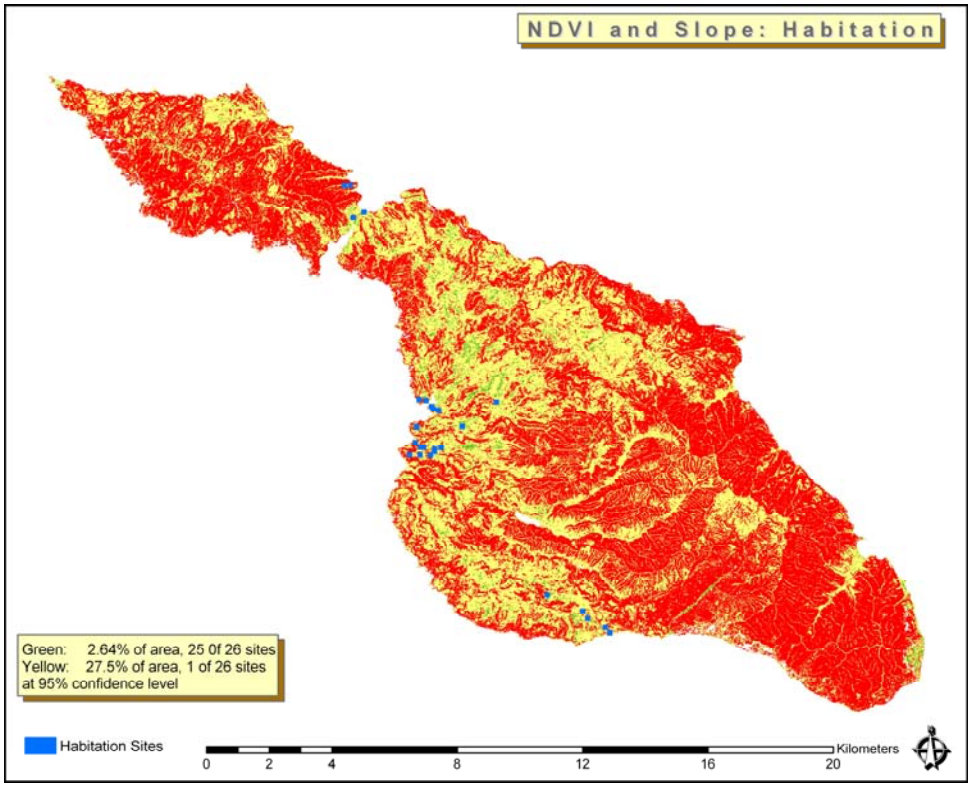
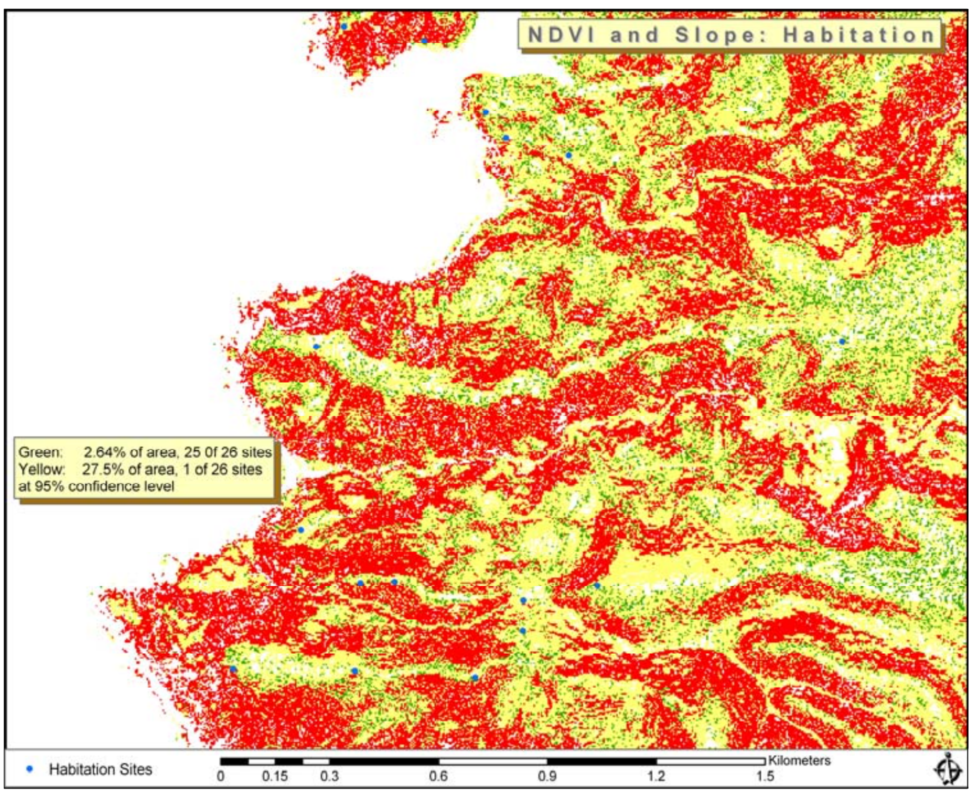


Fig. 10 Two-image layer signatures. Green areas are signatures for habitation sites as developed from both NDVI AND slope data, yellow areas are signatures developed from either NDVI OR slope data, blue dots are known habitation sites from which signatures were developed.

Fig. 11 Close up of signature areas, showing locations of known habitation sites from which signatures were developed



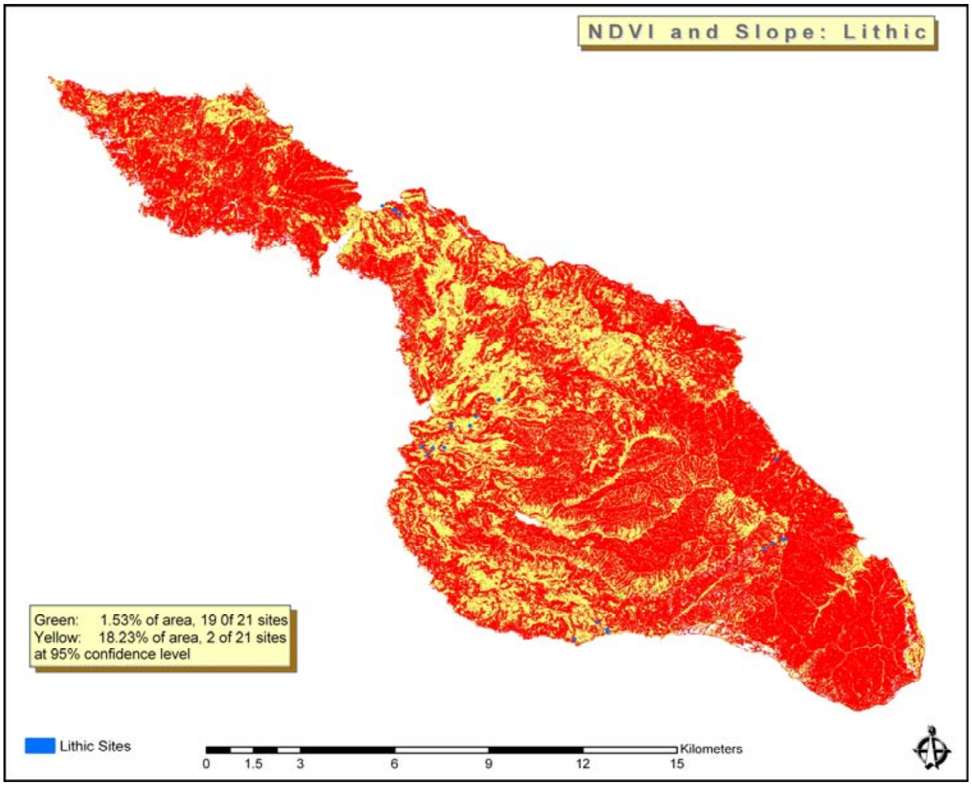
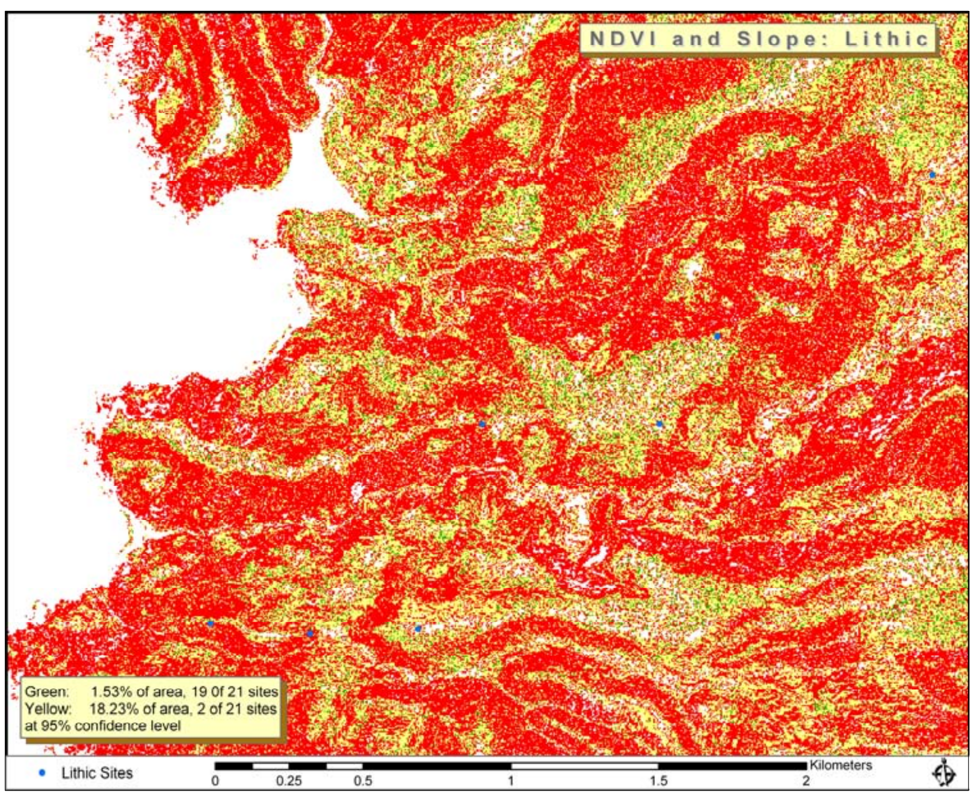


Fig. 12 Two-image layer signatures. Green areas are signatures for lithic sites as developed from both NDVI AND slope data, yellow areas are signatures developed from either NDVI OR slope data, blue dots are known lithic sites from which signatures were developed.

Fig. 13 Close up of signature areas, showing locations of known lithic sites from which signatures were developed



At the time that we submitted an interim report for this project in July of 2006, we had only recently acquired the XVV image, one that had already been scaled, and had not been able to develop signatures from it. Instead, then, we utilized only the X-band DEM (slope) image and the NDVI image to develop two-image signatures. Nonetheless, the signatures developed with only slope and NDVI were extremely encouraging, as can be seen in Figs. 10-13. For habitation sites, 25 of the 26 sites fall within the area that is common to both the 95% probability areas of slope and NDVI. These areas are seen in green in Figs. 10 (the entire island) and 11(a close-up). This is only 2.64% of the area of the island. For lithic scatter sites, the analysis indicates that 19 of 21 sites fall within the 1.53% of the area of the island that are included in 95% probability zones for both slope and NDVI (Fig. 12). Fig. 13 is a close-up of this.

After some time, we were successful in our attempts to acquire a version of the XVV image in which original magnitude values were preserved. This one we rescaled using the assumption that meaningful backscatter values would fall between 0 and 1.4, utilizing the rationale for this presented above. The results were quite interesting, and statistically quite impressive. Fig. 14 shows the results of signature development for lithic sites on Catalina Island, presented in the Boolean manner described above. Fig. 15 shows a close-up. Areas of yellow occupy 5.5% of the entire island, but indicate the locations of 100% of the lithic sites that were found during our three field surveys completed before September, 2007 if one assumes a 15 meter site radius, or 97.3% of the lithic sites if one assumes a site radius of 10 meters, or 84.09% of the known lithic sites if one assumes a site radius of 5 meters. It should be noted that the 44 site sample used to test the signatures includes the 15 sites that were used to create the signatures. Therefore, if the signatures are correct, we can see where the lithic sites on the island are located, and where they are not, given our assumptions, to a 95% degree of probability. The light green areas designate locations where any two of the image layers display signatures. Here, we see that only 0.02% of the island is covered by the lithic two-image layer signature, but that this area includes 50% of lithic sites with a 15 meter radius, 34.64 lithic sites with a hypothetical 10 meter radius, and 13.64 lithic sites with an assumed 5 meter radius. Three image layer signatures covered a miniscule 0.0032% of the area of the island, but indicate projected of almost 7% of 15-meter radius lithic scatters, 2.27% of 10-meter radius lithic scatters 5-meter radius lithic scatters. From a management standpoint, this would suggest immediately that the areas covered by lithic two and three image layer signatures should be set aside from development. The 1.535552 acres covered by the three-image layer signatures fall within the 9.5972 acres occupied by two-image layer signatures, which fall within the 2641.44 acres within the one-image layer signatures. The signature

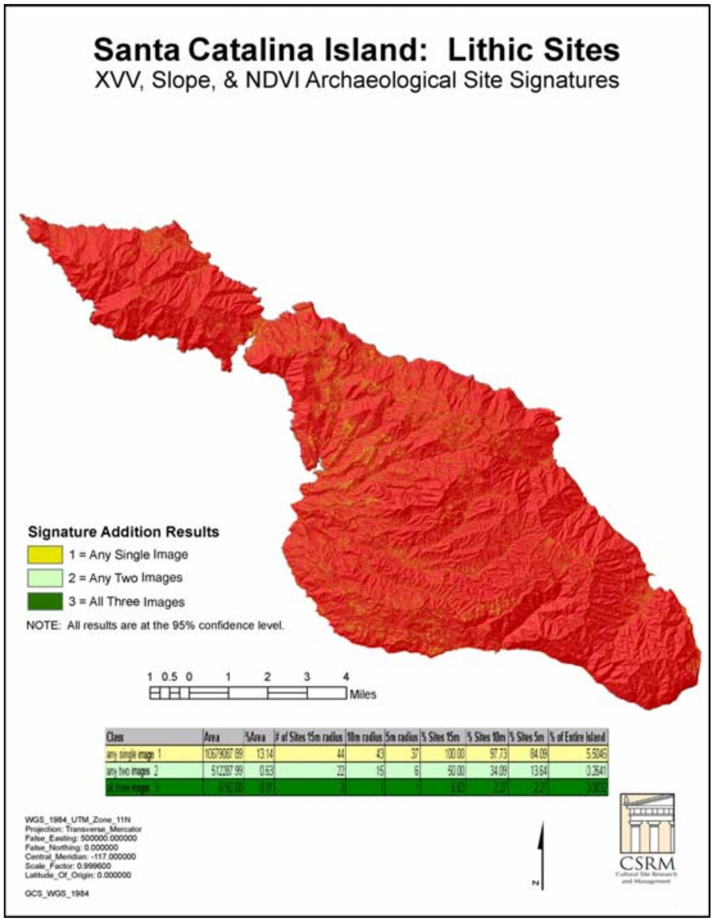
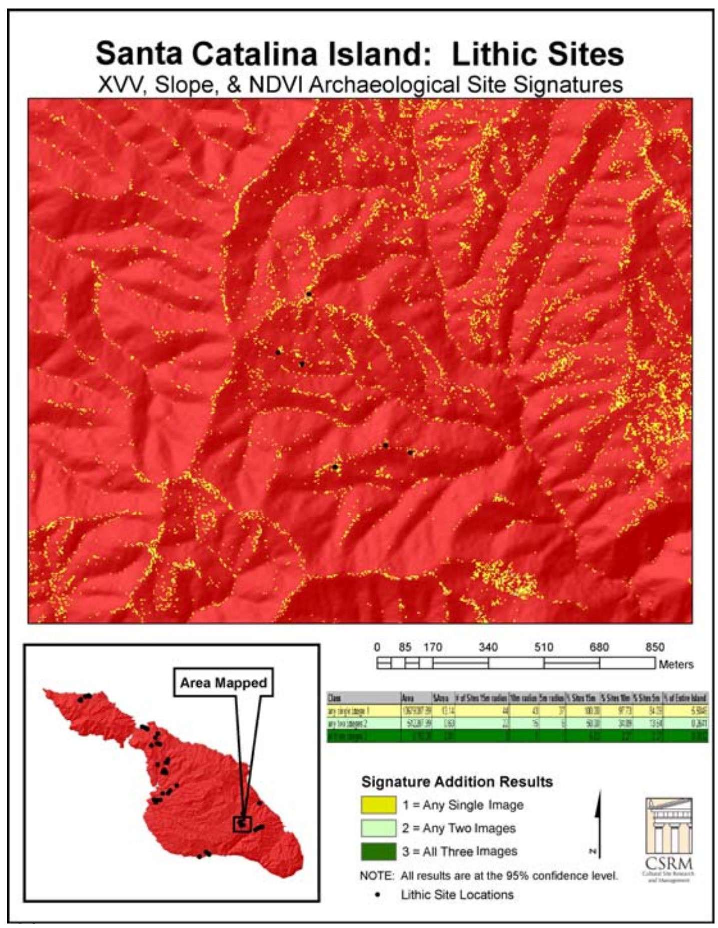


Fig. 14 Entire Island layout showing three-image lithic signatures

Fig. 15 Close up of three-image lithic signatures



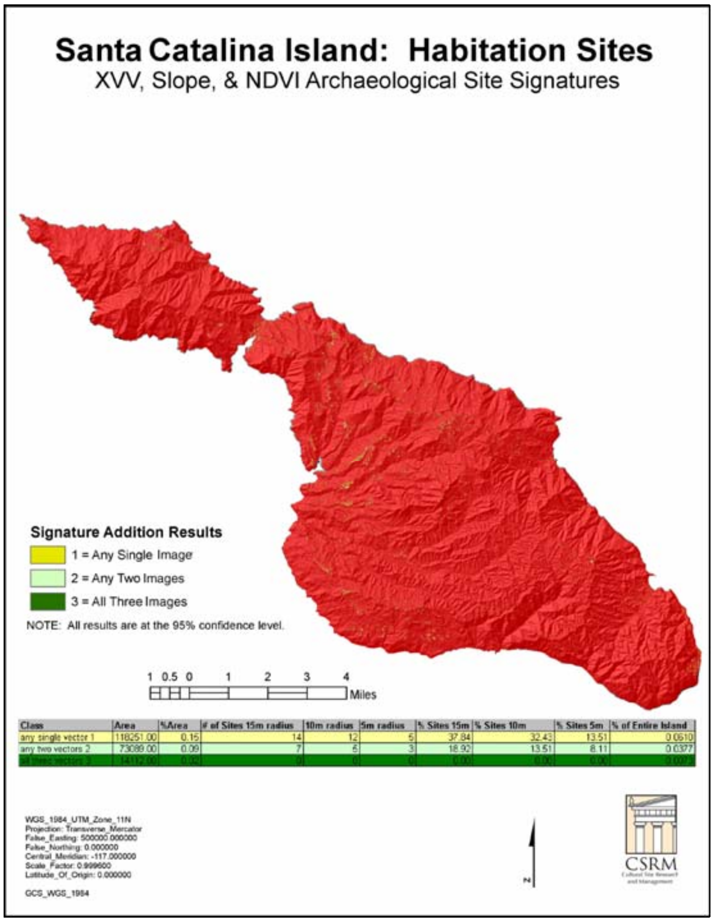


Fig. 16 Entire Island layout showing three-image habitation signatures

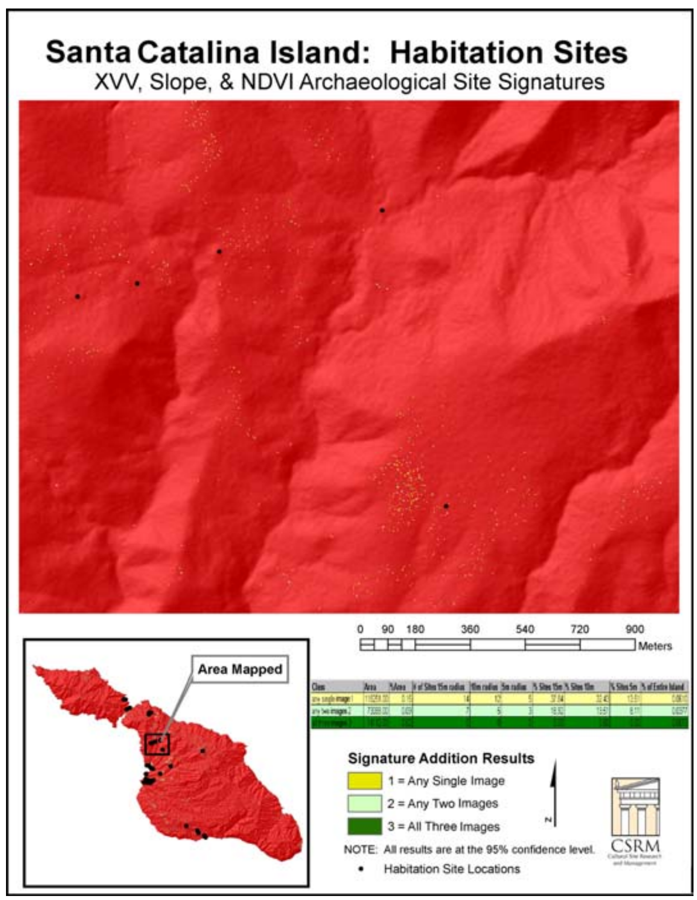


Fig. 17 Close up of three-image habitation signatures

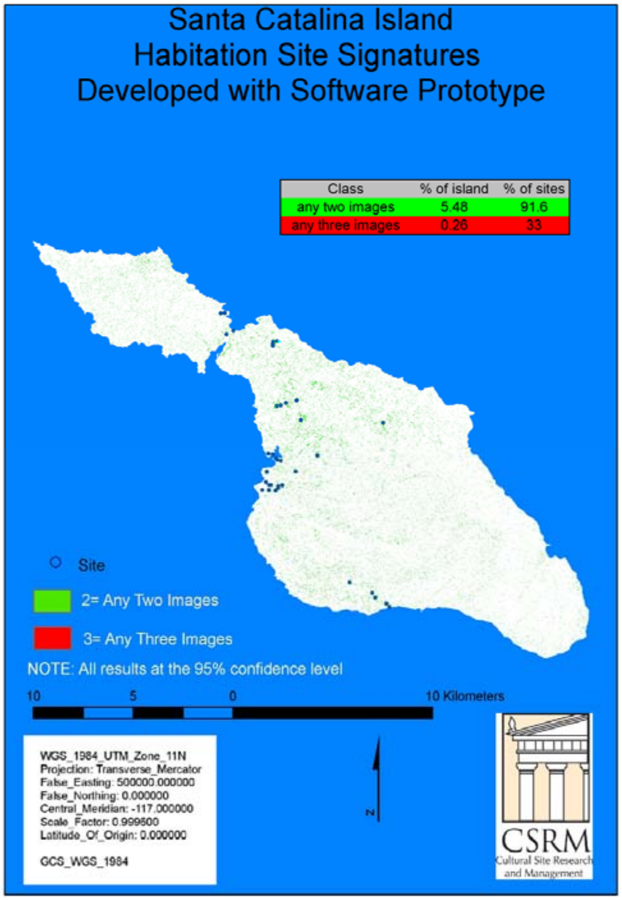


Fig. 18 Entire Island showing habitation site signatures developed with software prototype

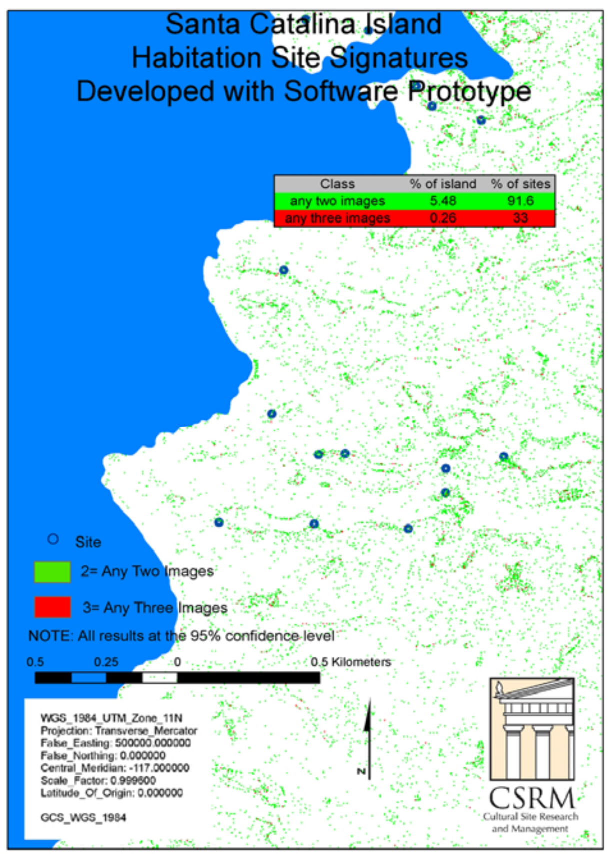


Fig. 19 Close up of habitation site signatures developed with software prototype

pixels are located somewhere within sites. The area occupied by any site will extend beyond the pixel signature to an extent that depends upon the size of the site and the precise location of the signature pixel or pixels within the site. However, 84% of the sites will extend no more than ten meters beyond the signature pixel, 98% no more than 20 meters, and 100% no more than 30 meters.

These results for habitation sites are seen in Fig. 16, in the context of the whole island, and Fig. 17, as a close up of a representative area. Yellow pixels, which are signatures created by any single image layer, cover only .06% of the island, but correspond in location with 37.84% of assumed 15-meter radius sites, 32.43% of assumed 10-meter radius sites, and 13.51% of hypothetical 5-meter radius sites. For the light green, two-image signatures, which cover .0377% of the island, these figures are 18.92%, 13.52%, and 8.11%. Finally, for three-image layer signatures covering .0073% of the island, no sites are found.

One notices immediately that these results seem consistent with those that were obtained with the original two-image layer signatures, but the areas covered by signature are sometimes much less, and the number of sites falling into these signatures are also less. Nonetheless, they suggest ways in which the landscape can be zoned in order to prevent damage to archaeological sites that are likely to be in certain areas. The researchers, however, are a bit concerned by the distribution of the three-image layer signatures, which are more scattered than those produced by two image layers. The scattering suggests, of course, radar "speckle." The attendant problem is just how meaningful this "speckle" is, that is, is it generated by characteristics of archaeological sites, and does it correspond closely in location to those sites.

The most recent effort to generate site signatures, this time utilizing our prototypical software that we developed from the analytical protocols suggests that while the scattering may indeed indicate speckle, that the speckle might have value in locating archaeological sites. The example here is given only for habitation sites, and was just completed prior to finalizing this report. Nonetheless, results are encouraging: Two-image signatures cover only 5.48% of the island, but contain 91.6% of site for which precise location is known, and three-image signatures cover only 0.26% of the island, but contain 33% of such sites. This is assuming that sites have a radius of 10 meters. Results are expected to improve in the future, as the software is used to run signature development protocols on images for which analytical parameters have been iteratively reset.

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Matt Hill
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Desiree Martinez
Collin O'Neill
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Jacob Comer
Lange Auman
Margaret Comer
Elizabeth Comer

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